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COMPARATIVE STUDY OF SPREAD SPECTRUM AND TIME MODULATED ULTRA-WIDE-BAND COMMUNICATIONS

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14. ABSTRACT
Ultra-wideband (UWB) communications have recently received much attention. A number of military and commercial applications of UWB have been suggested. An UWB transmitter generates signals of very large bandwidths (in excess of gigahertzs) by transmitting nanosecond or sub-nanosecond pulses at baseband in some randomized fashion. As a result, an UWB system is in fact a baseband spread spectrum (SS) system with a very large spreading gain. Many of the characteristics and advantages of conventional SS communications carry over to UWB. For instance, a typical UWB system is capable of supporting multiple users, is robust against jamming and interference, is robust against multipath fading, and is suitable for applications requiring low probabilities of interception and detection (LPI/LPD). On the other hand, the use of a very large bandwidth also imposes some new challenges, like wideband antenna design, acquisition design, and interference to other systems, in the design of UWB systems. The purpose of this report is to summarize the strengths and weaknesses of UWB radio with respect to the more conventional spread spectrum systems. This study used both theoretical and empirical data to arrive at a fundamental conclusion; UWB appears to be best suited for systems with fairly short link ranges and far outperforms its counterpart indoors.

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Comparative Study of Spread Spectrum and Time Modulated Ultra-Wideband Communications

Final Report

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Executive Summary

Ultra-wideband (UWB) communications has recently received much attention. A number of military and commercial applications of UWB have been suggested. An UWB transmitter generates signals of very large bandwidths (in excess of gigahertzs) by transmitting nanosecond or sub-nanosecond pulses at baseband in some randomized fashion. As a result, an UWB system is in fact a baseband spread spectrum (SS) system with a very large spreading gain. Many of the characteristics and advantages of SS communications carry over to UWB. For instance, a typical UWB system is capable of supporting multiple users, is robust against jamming and interference, is robust against multipath fading, and is suitable for applications requiring low probabilities of interception and detection (LPI/LPD). On the other hand, the use of a very large bandwidth also imposes some new challenges, like wideband antenna design, acquisition design, and interference to other systems, in the design of UWB systems. One major proponent of its recent popularity is the simplicity of an UWB radio. Since an UWB radio operates at baseband, no radio-frequency (RF) modulators and demodulators are needed. In addition, the use of a power amplifier can be avoided if the transmission range is small. The removal of the entire RF chain greatly simplifies and reduces the complexity and cost of the VLSI implementation of an UWB radio. Hence it is conceivable that small single-chip UWB communication units could be mass-produced at a very low per-unit cost. A large number of these UWB radios could be employed to set up a dense network. Therefore, most of the recent interest in UWB communications is for applications in personal area networks and sensor networks.

The goal of this project is to provide the Air Force with an independent evaluation and proof of concept on the usefulness and effectiveness of a form of UWB communications, referred to as Time-Modulated Ultra-Wideband (TM-UWB), for short to medium range communication in a battlefield environment. This report summarizes the findings obtained during the project. A functional comparison between UWB and traditional SS technologies based on published results in the open literature is presented. Three hypothetical application scenarios that are of interest to the Air Force were considered. A cooperative attack weaponry system, an aerial surveillance system, and a buried facility probing system were selected since they require a wide range of capabilities of the supporting communication systems. UWB and traditional SS signaling techniques were compared based on their relatively merits in these three scenarios. In particular, performance metrics, which summarize the various required communication capabilities in these application scenarios, were used as the basis for comparison. Experimental verification of the qualitative comparison between SS and UWB obtained from the preliminary analysis was performed. It was found that there is a strong potential advantage of using UWB in the buried facility probing system, for which a short-range, high-rate, low-power, wall-penetrating communication system is needed. For the other two scenarios of medium and long range communications, the advantage of using UWB, whether present at all, was not clear and needs to be further investigated.

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1 Introduction

Ultra-wideband (UWB) communications has recently received much attention. A number of military and commercial applications of UWB communications have been suggested. According to the most recent ruling by the Federal Communications Commission (FCC), a transmitter is classified as an UWB transmitter if it sends out a signal whose -10dB fractional bandwidth is larger than 20% or whose -10dB absolute bandwidth is larger than 500MHz. A similar definition was proposed by a DARPA panel on UWB requiring a -20dB fractional bandwidth of at least 25% or a -20dB absolute bandwidth of at least 1.5 GHz. Usually, an UWB transmitter generates this large fractional (or absolute) bandwidth by transmitting nanosecond or sub-nanosecond pulses at baseband in some randomized fashion. As a result, an UWB system is inherently a baseband spread spectrum (SS) system with a very large spreading factor (processing gain). Time hopping (TH) and direct sequence (DS) are the most common ways of spreading in UWB systems. Because of the very large processing gain, many of the characteristics and advantages of spread spectrum communications carry over to UWB. For instance, a typical UWB system is capable of supporting multiple users, is robust against jamming and interference, is robust against multipath fading, and is suitable for applications requiring low probabilities of interception and detection (LPI/LPD). On the other hand, the use of a very large bandwidth also imposes some new challenges, like wideband antenna design, acquisition design, and interference to other systems, in the design of UWB systems.

While UWB has long been used in radar applications, one of the major proponents of its recent popularity in communications is the simplicity of an UWB radio. Since an UWB radio operates at baseband, no radio-frequency (RF) modulators and demodulators are needed. In addition, the use of a power amplifier can be avoided if the transmission range is small. The removal of the entire RF chain greatly simplifies and reduces the complexity and cost of the VLSI implementation of an UWB radio, since RF components are usually the most space, power, and cost consuming portions of a typical wireless radio. Hence, it is conceivable that small single-chip UWB communication units could be mass-produced at a very low per-unit cost. A large number of these UWB radios could be employed to set up a dense network. Therefore, most of the recent interest in UWB communications is for applications in personal area networks and sensor networks.

The goal of this project is to provide the Air Force with an independent evaluation and proof of concept on the usefulness and effectiveness of a form of UWB communications, referred to as Time-Modulated Ultra-Wideband (TM-UWB), for short to medium range (100m-10km) communication in a battlefield environment. This study includes a literature search of experimental studies for both TM-UWB and SS. Current SS experimental results will be the basis for defining the physical experimentation with the TM-UWB system. The experimental study will include analyzing propagation constraints (indoors and outdoors) by varying power, line of sight, pulse integration techniques, receiver filtering techniques, and pulse coding techniques.

2 Overview of Spread Spectrum Communications

In conventional systems, the term *wideband* implies a large modulation bandwidth and thus a high data transmission rate. Spread Spectrum (SS) [1, 2] is a signaling technique that generates a signal whose spectrum is much wider than the bandwidth required to convey the information carried on that signal. Spreading the signal bandwidth over a much wider range enables in the generation of a signal that is more covert, has higher immunity to interference effects, and has improved time-of-arrival resolution. Different SS techniques have been widely employed in military and commercial communication systems. In the following, we review two of the most common SS modulation techniques, namely direct sequence (DS) and frequency hopping (FH).

2.1 Direct Sequence Spread Spectrum (DS-SS)

A direct sequence spread spectrum system employs a high-speed pseudo-noise (PN) sequence, usually referred to as a *signature* or *code* sequence, along with the basic information being sent, to modulate a RF carrier. The high-speed code sequence is used directly to modulate the carrier, thereby directly setting the transmitted RF bandwidth. The PN sequence generated at the modulator is often used in conjunction with phase-shift-keying (PSK) modulation to shift the phase of the PSK signal in a pseudorandom manner.

Schematic diagrams of a DS-SS communication system employing a quadrature phase-shift keying (QPSK) modulator and the corresponding DS-SS demodulator are shown below in Figures 1 and 2, respectively. DS-SS has found wide applications in commercial (e.g. IS-95) and military (e.g. GPS) communication systems.

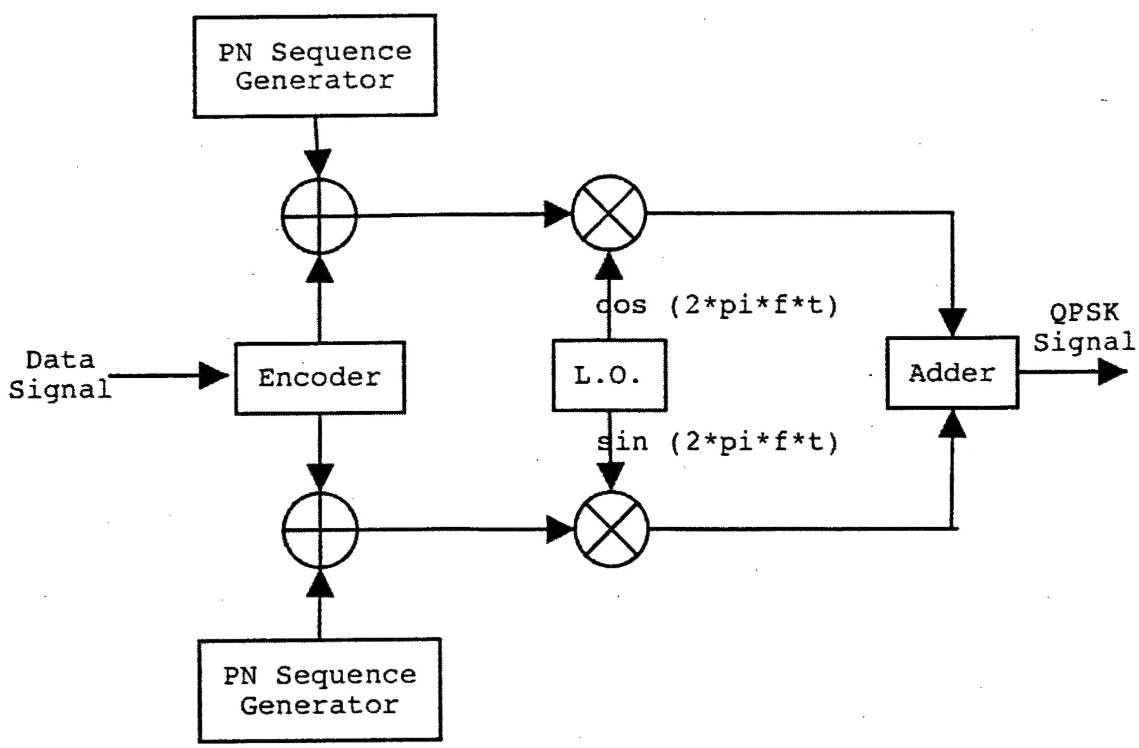

Figure 1: Schematic diagram of a DS-SS transmitter, employing QPSK.

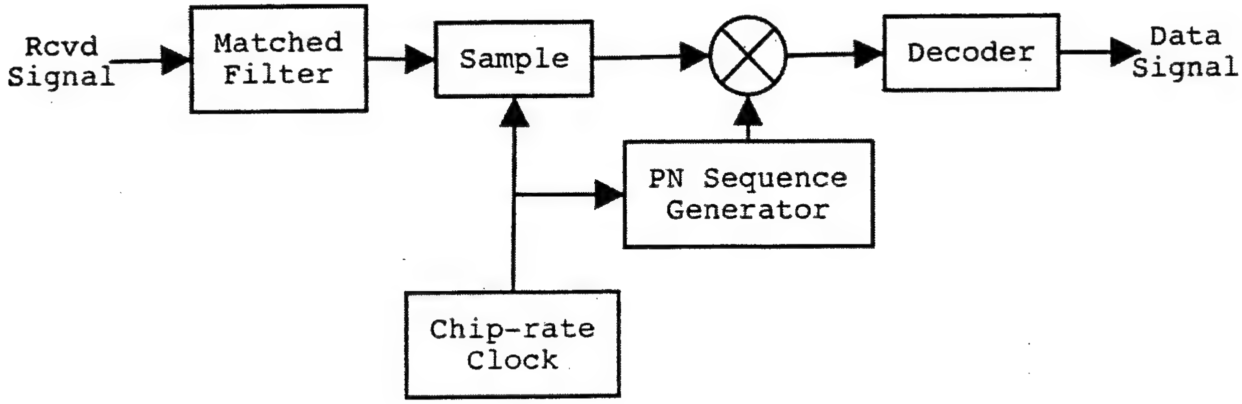

Figure 2: Schematic diagram of a DS-SS receiver.

2.2 Frequency Hop Spread Spectrum (FH-SS)

In a frequency-hopped spread spectrum system, the available channel bandwidth is subdivided into a large number of contiguous frequency slots. In any signaling interval, the transmitted signal occupies one of the available frequency slots. The selection of the frequency slot in each signaling interval is made in a pseudo-random manner according to the output from a PN sequence generator. Figure 3 shows the block diagram of a FH-SS transmitter. The block diagram of the FH-SS receiver is shown in Figure 4.

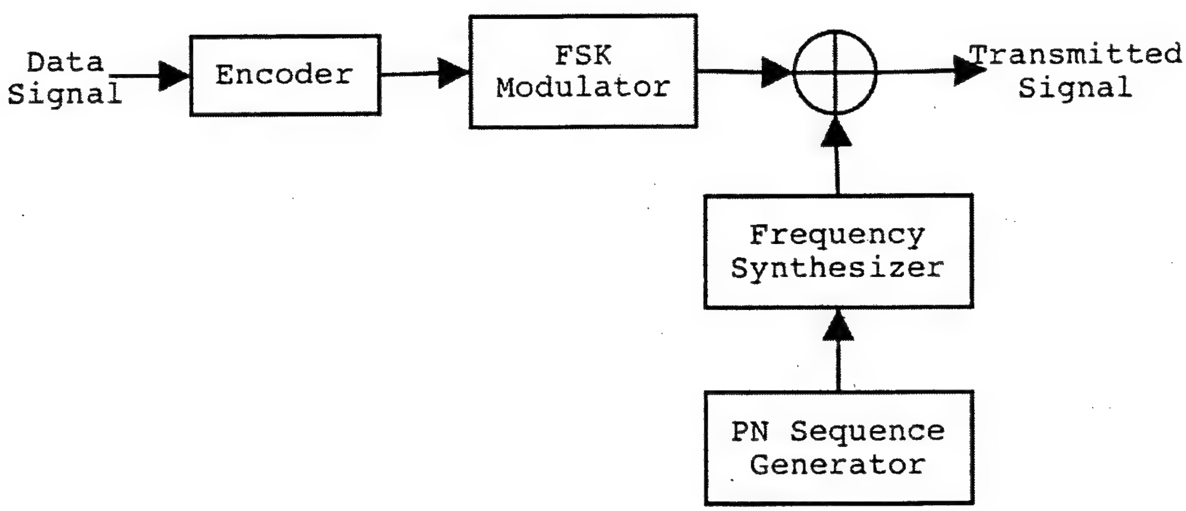

Figure 3: Schematic diagram of a FH-SS transmitter.

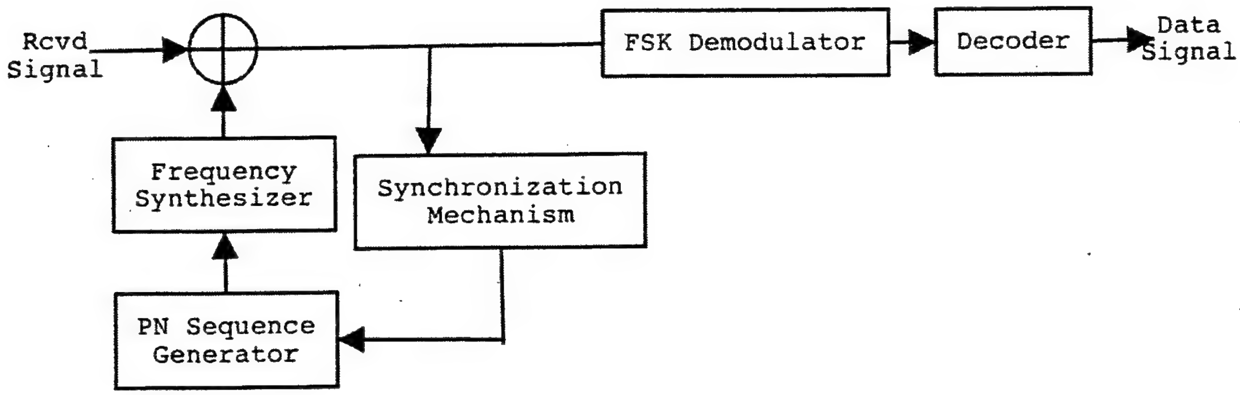

Figure 4: Schematic diagram of a FH-SS receiver.

The modulation format employed in a FH-SS system is usually either binary or M-ary frequency shift keying (FSK). For example, if binary FSK is employed, the modulator selects one of two frequencies corresponding to the transmission of either a 1 or a 0. The resulting FSK signal is translated in frequency by an amount that is determined by the output sequence from the PN generator, which in turn is used to select a frequency that is synthesized by the frequency synthesizer. This frequency is mixed with the output of the modulator and the resultant frequency-translated signal is transmitted over the channel. Like DS-SS, FH-SS also finds wide applications in commercial (e.g. Bluetooth) and military (e.g. SINGAR radio) communication systems.

2.3 Present State of Spread Spectrum Applications

Spread spectrum was originally developed for use in the development of military guidance and communication systems. By the end of World War II, achieving resistance to jamming using spectrum spreading was a familiar concept to radar engineers. Most of the research on spread spectrum communications that followed was aimed at the development of highly jam-resistant communication systems. However, there emerged various other applications such as multiple access communications, high-resolution ranging and energy density reduction. In 1985, the Federal Communications Commission (FCC) allowed spread spectrum's unlicensed commercial use in three frequency bands: 902-928 MHz, 2.4000-2.4385 GHz and 5.725-5.850GHz.

The enhancement in performance obtained from a DS-SS signal through the processing gain and the coding gain is used to enable many DS-SS signals to occupy the same channel bandwidth provided that each signal has its own distinct PN sequence. This type of digital communication, in which each transmitter-receiver pair has a distinct PN code for transmitting over a common channel bandwidth, is called code division multiple access (CDMA) [11, 12]. Direct sequence CDMA has been adopted as one multiple-access method for digital cellular voice communications in North America. Proposed and developed by Qualcomm, this system has been standardized and designated as TIA/EIA-95 (commonly referred to by its interim standard designator: IS-95) [13] by the Telecommunications Industry Association (TIA) for use in the 800 MHz and in the 1900 MHz frequency bands. This system uses a nominal bandwidth of 1.25MHz for transmission from a base station to the mobile receivers (called the forward link) and another

channel with a bandwidth of 1.25 MHz is used for signal transmission from the mobile receivers to the base station (called the reverse link). The signals transmitted in both the forward and the reverse links are DS-SS signals with chip rates of approximately 1.23 Mchips/s. Extensions of the DS-CDMA techniques to wider bandwidths, such as cdma2000 and WCDMA, have also been adopted in third generation cellular standards.

Frequency-hopped spread spectrum has been extensively employed in covert military communication systems. FH spread spectrum signals are used in communication systems that require anti-jam protection and in CDMA. FH-SS has also been employed in Bluetooth, a de facto standard and specification for low-cost, short-range radio links between mobile computers, phones and other portable devices. The Bluetooth radio is built into a small microchip and operates in the 2.4 GHz ISM band. The Bluetooth radio accomplishes spectrum spreading by frequency hopping in 79 hops displaced by 1 MHz, starting at 2.402 GHz and ending at 2.480 GHz. Each Bluetooth device is classified into three power levels, power classes 1, 2 and 3. Power class 1 devices are designed for long-range (up to 100m) with a maximum output power of 20 dBm. Class 2 devices are for medium-range (around 10 m) with a maximum output power of 4 dBm and power class 3 devices are short-range devices (up to 10 cm), with a maximum output power of 0dBm.

3 Overview of Ultra-Wideband Communications

Ultra-wideband (UWB) is a form of spread spectrum techniques which spread the information signals to bandwidths that are usually much larger than those generated by traditional spread spectrum systems described above. UWB technology has its origins in the work of Gerald F. Ross in the field of time-domain electromagnetics, in the 1960s, to fully describe the transient behavior of a certain class of microwave networks through their characteristic impulse responses. Through the 1980s, UWB was employed by the radar research community for the development of short-range, high-resolution sensing applications. High power military radar was one of the earliest applications of UWB technology. Other military applications included covert communications, due to the low probability of intercept capability of UWB signals, and ground penetrating radar, due to the use of a very wide band of frequencies, for detection of buried mines. The term *ultra-wideband* was first applied around 1989 by the U.S. Department of Defense and this technology was earlier referred to as baseband carrier-free or impulse radar. Since the 1990s, there has been a lot of interest, both academic and industrial, regarding the application of UWB technology for wireless communications, which came to be known as *impulse radio* [3,4].

The techniques for generating UWB signals have been studied for over three decades. A number of spreading techniques have been suggested. These techniques include employing the direct sequence, time hopping, and multi-carrier approaches. By far, time-hopping UWB appears to be the most popular choice among the three. Here, we are primarily concerned with time-hopping UWB, which is also referred to as *time-modulated UWB*.

3.1 Time-Modulated UWB

Time-modulated UWB (TM-UWB) is a communication technique in which no sinusoidal carrier is used to raise the signal to a specific frequency band. Instead, communication is achieved with a time-hopping (TH) baseband signal composed of sub-nanosecond pulses (commonly referred to as *monocycles*) [3-6]. Because of the use of narrow pulses, TM-UWB is also referred to as *impulse radio*. For instance, a typical TM-UWB transmitter emits ultra-short Gaussian monocycles with tightly controlled pulse intervals. These pulse widths are between 0.2 and 1.5ns and the pulse-to-pulse intervals are between twenty-five and one thousand nanoseconds. Channelization is obtained by the PN time-hopping sequences. Modulation in TM-UWB systems is often accomplished through time-shifting (also called *dithering*) these pulses, thereby resulting in a form of pulse position modulation (PPM). The bandwidth of such a transmitted signal varies from near dc to several gigahertz. Thus, the impulse radio signal undergoes distortions in the propagation process even in benign propagation environments.

A TM-UWB receiver directly converts the received RF signal into a baseband digital or analog output signal. A front-end correlator coherently converts the electromagnetic pulse train to a baseband signal in a single stage. Circuit complexity is greatly reduced as there are no radio frequency stages. A single bit of information is spread over multiple monocycles. The receiver coherently sums the proper number of pulses to recover the transmitted information. Schematic diagrams of the TM-UWB transmitter and receiver are shown below in Figures 5 and 6, respectively.

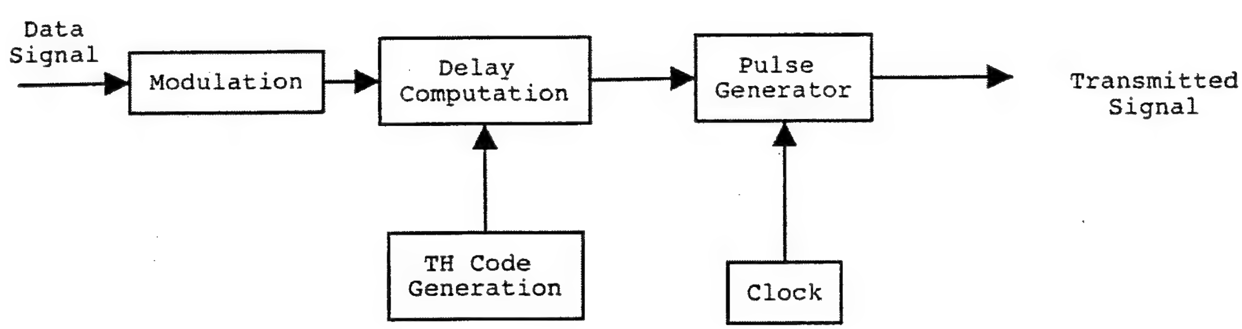

Figure 5: Schematic of a TM-UWB transmitter.

Attempts have been made to study and model the channel characteristics when UWB signaling is used for communication in both indoor and outdoor environments, taking into account the distortion an UWB signal undergoes due to dense multipath [7-9, 21-23].

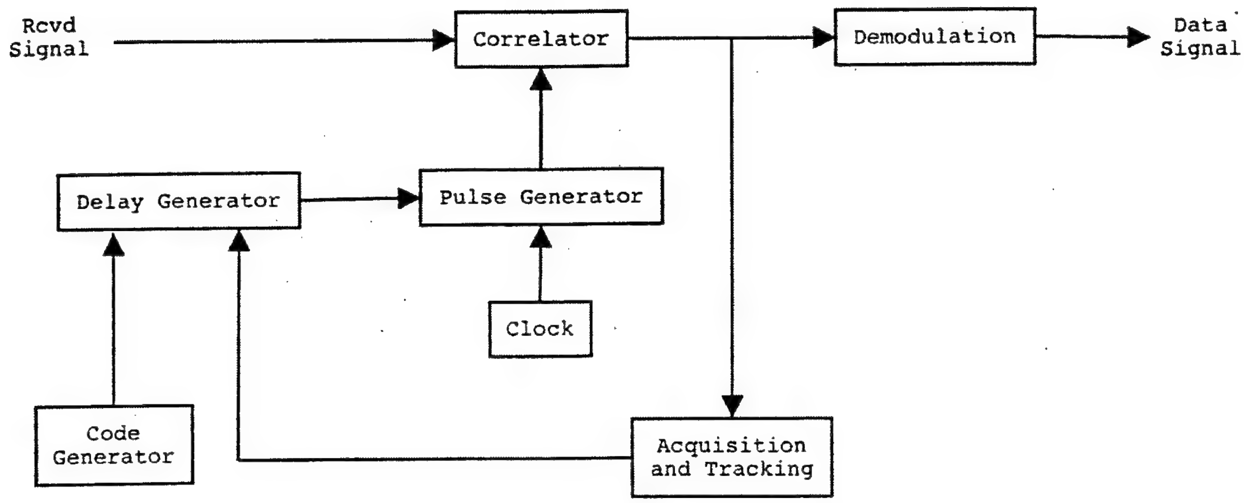

Figure 6: Schematic of a TM-UWB receiver

3.2 TM-UWB Signal Format

The implementation of the Gaussian monocycle is the most basic element of TM-UWB technology. The Gaussian monocycle is a commonly accepted model for the pulse generated by a typical UWB communication system [3-5]. A typical UWB antenna causes a derivative action on a Gaussian pulse that is generated with the help of a step-recovery diode. Hence the transmitted Gaussian monocycle is nominally represented by the first derivative of a Gaussian function:

$$w(t) = 2\sqrt{e}A\pi t f_c \exp\left[-2(\pi t f_c)^2\right],$$

where A determines the amplitude of the pulse and f_c determines its center frequency. We note that the monocycle is a wide bandwidth signal, with the center frequency and bandwidth being completely dependent upon the width of the monocycle. A plot of the Gaussian monocycle is shown in Figure 7 and its spectrum is shown in Figure 8.

A model for the received signal using Hermite polynomials has been described in [7]. The shape of the transmitted monocycle $w(t)$ is modified to $w_{rec}(t)$ by the channel and received antenna. A typical model for the received pulse shape $w_{rec}(t)$ is given by

$$w_{rec}(t) = A\left[1 - 4\pi\left(\frac{t}{\tau_m}\right)^2\right]\exp\left[-2\pi\left(\frac{t}{\tau_m}\right)^2\right],$$

where τ_m is the nominal pulse width. The plot of a typical ideal received monocycle is shown in Figure 9 and its spectrum is shown in Figure 10.

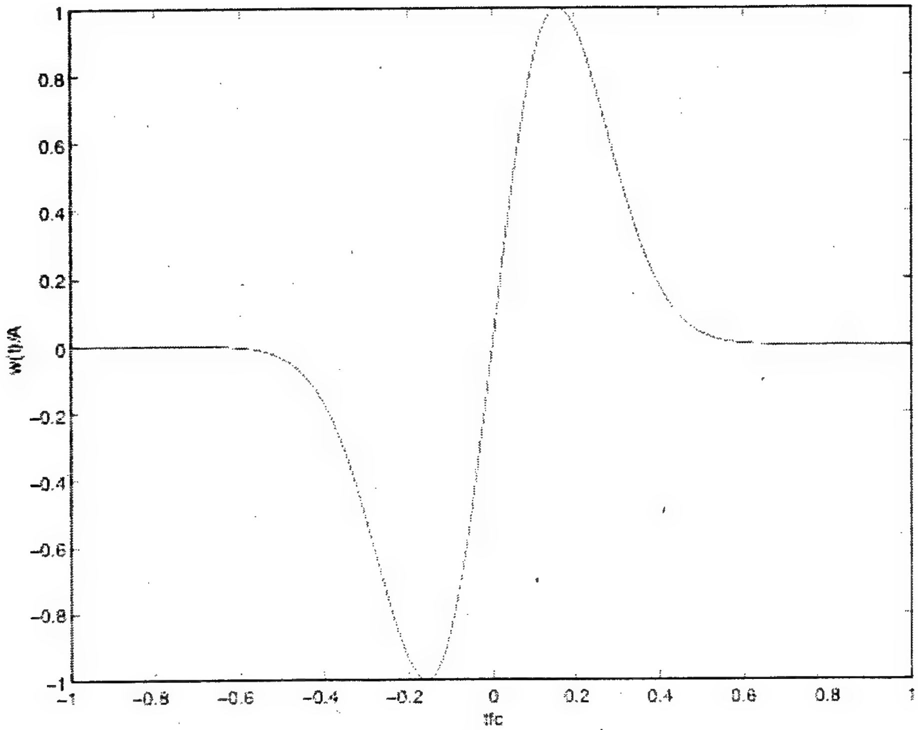

Figure 7: Normalized plot of the Gaussian monocycle.

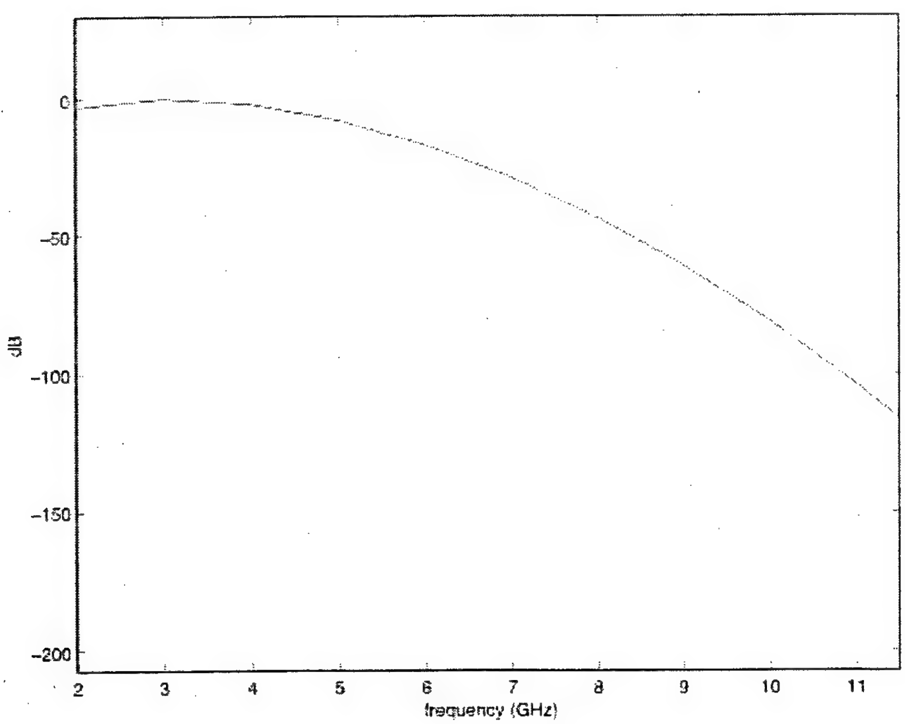

Figure 8: Spectrum of a transmitted Gaussian monocycle.

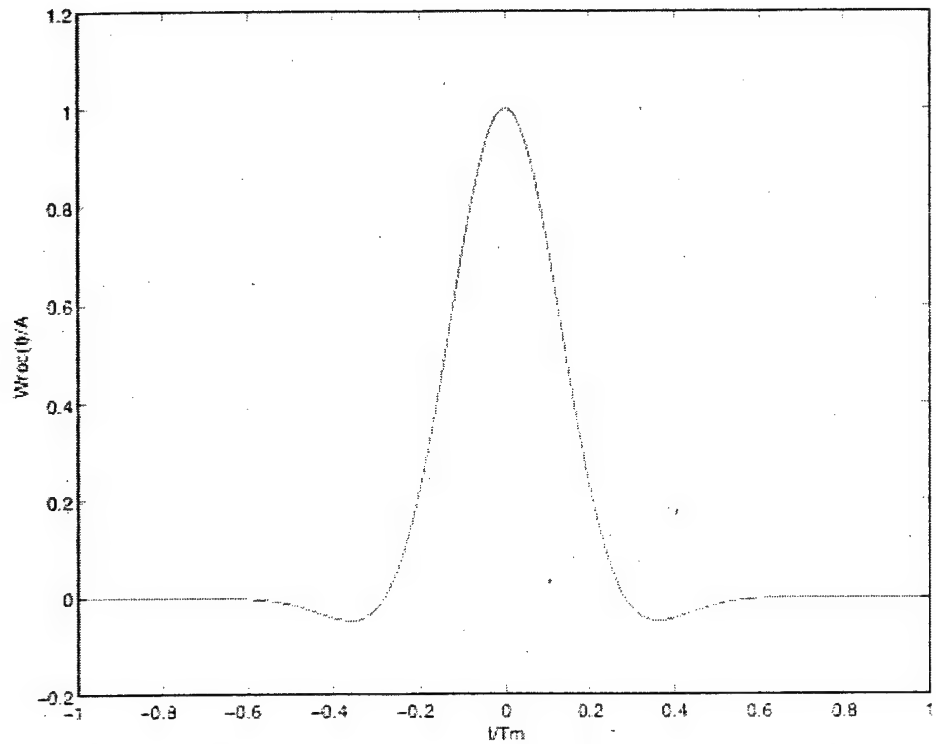

Figure 9: Normalized plot of an ideal received monocycle.

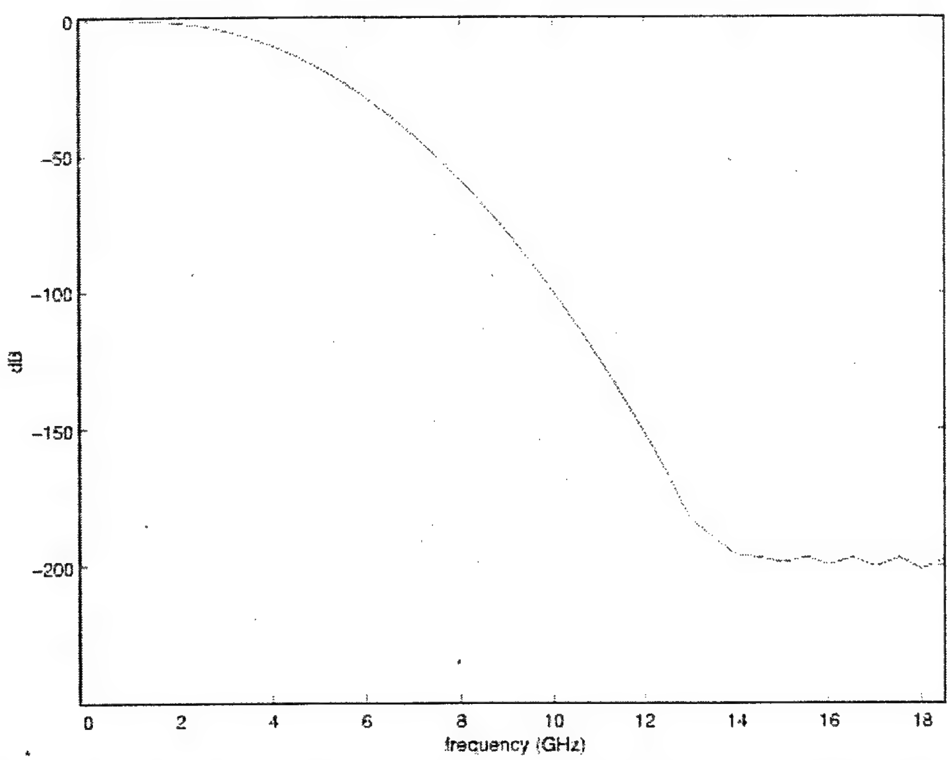

Figure 10: Spectrum of the ideal received monocycle shown in Figure 9.

As mentioned before, TM-UWB is a *carrierless* modulation technique. A long sequence of monocycles is employed to represent the information symbols. Thus a general UWB signal $s(t)$ can be represented as a sum of pulses shifted in time.

$$s(t) = \sum_{k=-\infty}^{\infty} a_k w(t - \tau_k),$$

where a_k and τ_k are the amplitude and the time shift corresponding to each individual pulse. The shifts τ_k's are usually several orders of magnitude larger than pulse width so that overlap in time of consecutive pulses does not take place.

However, when transmitting such sequences of pulses, care must be taken to ensure that the spectral quality of the transmissions remain intact. The spectrum of a monocycle pulse train has energy spikes at regular intervals. Varying the pulse intervals can eliminate these comb lines. The use of pulse position modulation and time hopping in TM-UWB systems varies the precise timing of transmission about the nominal position, hence smoothing the spectrum of the UWB signal.

3.3 TM-UWB Multiple Access Communications

Like many spread spectrum communication systems, an ultra-wideband impulse radio system can accommodate a number of simultaneous users. This multiple access capability is achieved by assigning different time hopping patterns to different users. More precisely, in a TH-UWB system, the kth user's impulse radio transmits a signal that is given by:

$$s_{tr}^{(k)}(t^{(k)}) = \sum_{j=-\infty}^{\infty} w(t^{(k)} - jT_f - c_j^{(k)}T_c - \delta d_{\lfloor j/N_s \rfloor}^{(k)}),$$

where $t^{(k)}$ is the kth user's transmitter clock time and T_f is the pulse repetition time. To avoid catastrophic collisions in multiple access, each transmitter is assigned a distinctive time-shift pattern $\{c_j^{(k)}\}$ called a time-hopping (TH) sequence. These TH sequences are pseudorandom in nature and are periodic with period N_p. The TH sequence provides an additional time shift, besides the modulation, to each monocycle in the pulse train. For instance, the jth monocycle in the kth user's UWB signal undergoes an additional shift of $c_j^{(k)}T_c$ seconds. Each element of the TH sequence is an integer belonging to the set $\{0, 1, 2, \dots, N_{h-1}\}$ and hence the additional time shifts caused by the codes are discrete times between 0 and $N_h T_c$ seconds. Further, the value of $N_h T_c$ is chosen such that the fraction of the frame time over which time hopping is allowed, i.e. $N_h T_c / T_f$ is strictly less than one. This is done because a short interval of time is required to read the output of a monocycle correlator and to reset the correlator at the receiver. The parameter δ is the modulation factor and $\{d_i^{(k)}\}$ is the data sequence consisting of binary symbols (0 or 1). When the data symbol is 0, no additional time shift is added to the monocycle and a time shift of δ is added to the monocycle when the symbol is 1. The system under consideration is an over-sampled modulation system with N_s monocycles transmitted per symbol and the modulating data symbol changes only every N_s hops. As a consequence, the data transmission rate of a transmitter is $1/N_s T_f$ bits per second.

Apart from eliminating collisions in multiple accessing, the TH code has the effect of smoothing the power spectral density of the transmitted signal. Since the TH sequence is periodic with period N_p, the transmitted signal is periodic with period $N_p T_f$ in the absence of data modulation. Thus the effect of the TH sequence is to reduce the power spectral density from the line spectral spacing of $1/T_f$ down to a spectral density with finer line spacing of $1/N_p T_f$. The data modulation further smoothes the power spectral density of the transmitted signal.

When K users are active in the multiple-access TM-UWB system, the composite received signal at the output of the receiver's antenna can be modeled as

$$r(t) = \sum_{k=1}^{N} A_k s_{rec}^{(k)}(t - \tau_k) + n(t),$$

where A_k represents the amplitude of the signal received from the k[th] transmitter, τ_k represents the combined effect of the time asynchrony between the clocks of k[th] transmitter and receiver and the propagation delay, and $n(t)$ represents other non-monocycle interferences such as receiver noise, which can be modeled as Gaussian noise. The expression for $s_{rec}(t)$ is similar to that of $s_{tr}(t)$ with the transmitted pulse $w(t)$ replaced by the received pulse shape $w_{rec}(t)$.

In [4] the error performance of TH-UWB multiple-access systems is studied. The performance for such systems is a function of the number of users K, the operating signal-to-noise ratio $SNR(K)$, and the modulation rate R_{mod}. The operating SNR is defined as

$$SNR(K) = \left\{ SNR^{-1}(1) + \tilde{M} R_{mod} \sum_{k=2}^{K} \left(\frac{A_k}{A_1} \right)^2 \right\}^{-1}$$

where $SNR(1)$ is the output SNR observed in a single-link scenario and $\tilde{M}$ is the modulation index. Defining the excess single-link power to be

$$\Delta P = 10 \log_{10} \left\{ \frac{SNR(1)}{SNR(K)} \right\}$$

and assuming perfect power control in the multiple-access system, i.e., $A_k = A_1$ for all k, the following equation relating the modulation rate and the number of users in terms of the excess single-link power results:

$$R_{mod} = \frac{1 - 10^{-\Delta P/10}}{\tilde{M}(K-1) SNR(K)}$$

For a fixed number of users K and a specified operating SNR, the achievable modulation rate is a monotone increasing function of the excess single-link power ΔP. Similarly, for a given modulation rate and the operating SNR, the number of users that the TH-UWB multiple-access system can support is a monotone increasing function of ΔP :

$$K = \left\lfloor \frac{1 - 10^{-\Delta P/10}}{\tilde{M} R_{mod} SNR(K)} \right\rfloor + 1$$

The two expressions above give the upper bound on the modulation rate for a fixed number of users and the upper bound on the number of users for a fixed modulation rate, when a particular level of SNR performance is specified. Assuming that the noise due to the multiple access interference and the receiver noise are both Gaussian, a plot showing the achievable modulation rate versus ΔP, when there are 100 users in the TM-UWB multiple-access system is shown below in Figure 11. This plot assumes that the noise due to the multiple access interference and the receiver noise are both Gaussian. For example, it is seen from the figure that the maximum possible modulation rate is about 2.3 Mbps for the bit error rate (BER) requirement of 10^{-6}.

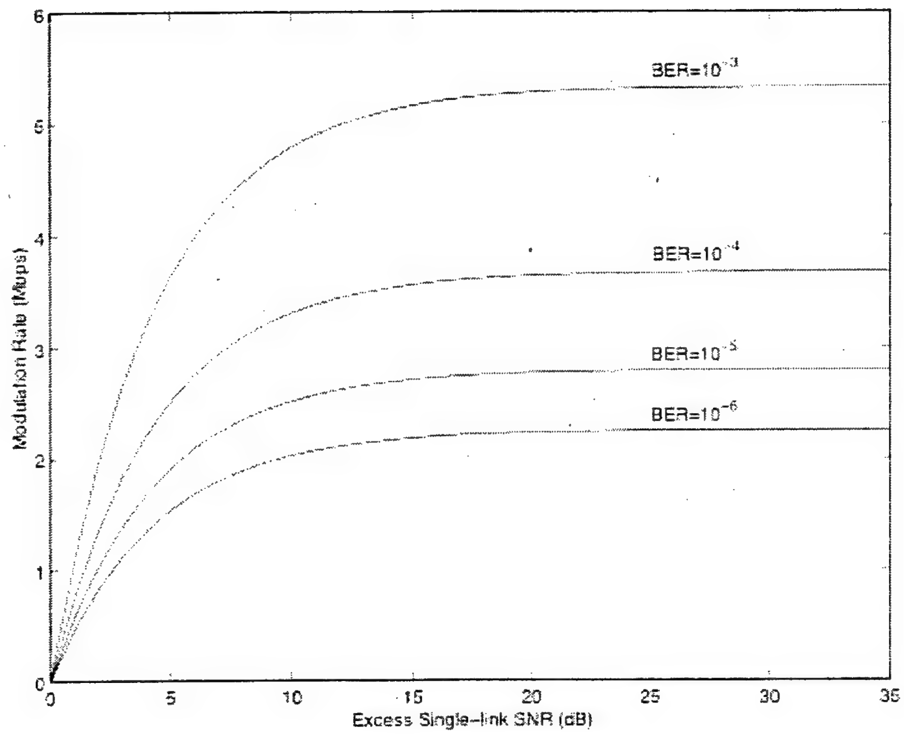

Figure 11: Modulation Rate versus excess single-link power at four different bit error rates, when there are 100 users in the TM-UWB multiple-access system.

Similarly, the number of users that the TM-UWB multiple-access system can support theoretically at different acceptable levels of bit error rate performance is shown in Figure 12. The modulation rate in this case has been set at 19.2kbps. For example, for a BER of 10^{-6} and a modulation rate of 19.2 kbps, the TM-UWB implementation can theoretically support in excess of 10,000 users. However, it is noted that a very high transmission power (at least 10dB above the power needed in a single-user system) is required to support this large number of users. With a reasonable excess single-link power of 3dB, a few thousand users can be supported.

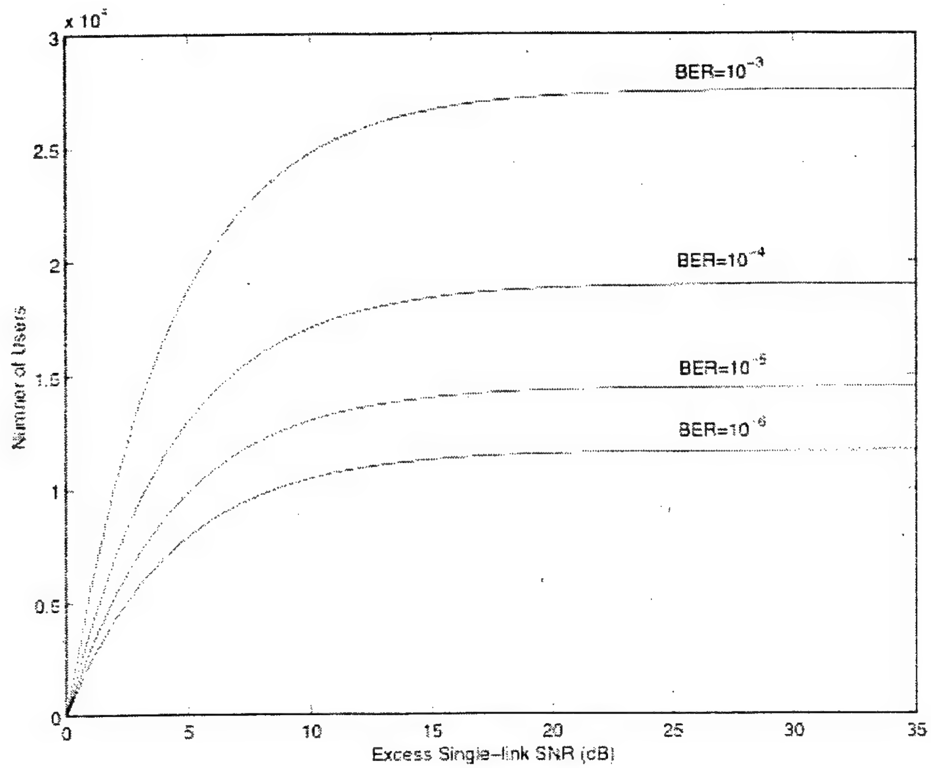

Figure 12: Number of users that the system can support versus excess single-link power at four different bit error rates, for modulation rate of 19.2 kbps.

3.4 Medium Access Control in TM-UWB Communications

The current focus on TM-UWB is its applicability in the short-range and high data rate *ad hoc* network environments, such as a wireless personal area network (WPAN). In such systems, the main approach to provide multiple access is through a medium access control (MAC) protocol. Current efforts on the MAC protocol for UWB communications are focused on determining whether any standard protocol is applicable or a new protocol is needed. For instance, the IEEE 802.15 High Rate Alternative PHY Study Group 3a (SG3a) is working on a standard for the MAC protocol using UWB as the physical layer. Currently, MAC protocols that are being considered for use with UWB are:

1) MAC protocol of IEEE 802.15.3 (WPAN),
2) MAC protocol of IEEE 802.11e (WLAN), and
3) MAC protocol of HIPERLAN/2 DM (Direct Mode).

The first option is mainly considered as a MAC protocol for UWB since the IEEE 802.15 Study Group 3 (SG3) has been standardizing MAC protocol for short range (10m) and high data rate (maximum 55Mbps) communications at 2.4 GHz carrier frequency. SG3a has decided to modify the SG3 MAC for UWB communications. This protocol suggests the use of both contention and contention-free access within a structure of super frames. However, it has been stated that this MAC protocol is inefficient because it is based on the CSMA/CA protocol, which could cause delays in accessing the channel. The second protocol is an enhanced version of the MAC protocol of the IEEE 802.11 standard that provides provisions for prioritized channel access and

quality of service (QoS). In this MAC protocol, contention-free periods are dynamically inserted during the contention period for QoS-guaranteed traffic and higher priority packets so that they have a higher probability of getting access of the channel. The third suggested protocol is almost the same as the first one. However, the structure of the super frame is different, the channel access method is slotted ALOHA, and it uses a fixed-size super frame.

In the open literature, another MAC protocol, which focuses on reducing the time for UWB signal acquisition, has been suggested [16]. In this protocol, after the communication link is established between two nodes, the link is maintained until one node leaves the communication area. If there is no packet to transmit, control information is transmitted using lower power to maintain the link. This protocol can reduce the acquisition overhead, but it may create more interference to other nodes in an environment having many users. In addition, it prevents a node from acquiring signals from nodes other than the one with which it is maintaining a link. Furthermore, even at reduced power levels, the link maintenance signals may result in a significant reduction in battery life in portable devices.

All of the protocols mentioned above are designed to operate within a small cluster, usually referred to as a *piconet*, of UWB communicators. Multiple access between different piconets is usually provided by using the inherent multiple-access capability of the UWB systems.

3.5 Effect of UWB Interference on GPS Receivers

There has been a considerable amount of interest in evaluating the interference effects of UWB signaling on other communication systems [19, 20]. In February 2001, the National Telecommunications and Information Administration (NTIA) of the US Department of Commerce released a report [14] detailing their investigations measuring the interference from a representative set of UWB signals on a select group of GPS receivers. Initially, NTIA tested two GPS receivers, a C/A (coarse/acquisition) code tracking receiver and a semi-codeless receiver architecture, which is used for applications requiring more precision. In a follow-on measurement study [15], measurements were performed on a GPS receiver employing a narrowly spaced correlator architecture and an aviation GPS receiver also employing the C/A code receiver architecture. NTIA used the following operational metrics to assess interference to GPS receiver operations:

- *Break-lock (BL) Point:* A break-lock point is the point at which loss of signal lock starts occurring between the GPS receiver and the satellite. Thus the BL point represents the level of the UWB signal power that causes a GPS receiver in tracking mode to re-enter acquisition mode. For the purpose of analysis, NTIA defined the BL point to be 1 dB above the maximum UWB signal power, where the receiver is able to maintain lock during the entire BL measurement duration.

- *Reacquisition time (RQT):* The reacquisition time is the amount of time it takes a GPS receiver, which has been tracking a GPS signal, to reacquire the signal after synchronization is lost. To span the full range of existing and potential UWB signals, three parameters, namely pulse repetition frequency (PRF), pulse spacing, and gating

were varied and 32 different permutations were chosen. NTIA performed testing to determine the interference thresholds of the GPS receiver. The GPS signal and background noises were generated with a multi-channel GPS simulator (Nortel model STR2760) and a noise diode, respectively.

The UWB signals and GPS noise measured signals were expressed in terms of a 20-MHz bandwidth (centered at 1575.42 MHz), and power measurements were expressed as RMS power levels. These measurements gave values of the RMS power level for interference using the thresholds for BL and RQT for each of the different possible UWB signal variations. It was demonstrated by NTIA that independent UWB pulses of sufficient amplitude would saturate one or more elements in the GPS receiver during the pulse period. If the pulses are relatively short and are of a low duty cycle, they will not seriously degrade GPS performance. The interference effect is independent of the amplitude of the pulses as long as it is below the peak pulse power limit of the receiver. The conclusion arrived at by NTIA is that GPS performance is relatively robust to pulse-like emissions.

The US Department of Transportation (DOT) sponsored a GPS/UWB compatibility study at Stanford University, wherein measurements considered a UWB signal with a PRF of 100 kHz and arrived at the same conclusion as the NTIA. As long as the PRF of the UWB emission is no greater than 100kHz, and the output level of the UWB emission is low enough so as not to overload the front end of the GPS receiver, interference to GPS from UWB operation is not likely. Based on the test data, FCC decided that UWB devices could operate at the Part 15 general emission limits, provided the PRF does not exceed 100 kHz, without causing interference to GPS reception. Hence, ground penetrating radars with PRFs less than 100 kHz are not an interference concern to GPS receivers.

3.6 Present State of TM-UWB Applications

The Federal Communication Commission (FCC) defines ultra-wideband as any technology that has spectrum that occupies bandwidth greater than 20% of center frequency or greater than 500 MHz. FCC conducted a study which focused on addressing industry, military, and public community concerns on the commercialization of UWB technology. Primary concerns included health risks and interference with existing radio technologies. In February 2002, the FCC adopted a First Report and Order regarding the revision of Part 15[1] of the Commission's rules pertaining to ultra-wideband transmission systems. The FCC report uses the -10 dB emission points to determine the bandwidth and the center frequency of the UWB emission. The report categorizes UWB devices into three types:

1) imaging systems, including ground penetrating radar systems (GPRs),
2) vehicular radar systems, and
3) communications and measurement systems.

[1] Part 15 sets out the regulations under which an intentional, unintentional, or incidental radiator may be operated without an individual license. It also contains the technical specifications for various types of devices. These technical specifications include absolute maximum radiated and conducted limits, in addition to the requirements stipulating that no harmful interference may result from the operation of a Part 15 device. In addition, the rules contain administrative requirements and other conditions relating to the marketing of Part 15 devices.

Different standards have been established for these three categories of devices depending upon their operational characteristics and their potential for causing interference to other radio services that are authorized to operate in their allocated frequency bands. The following discussion is a summary of the restrictions and operating guidelines outlined in the Order:

Imaging Systems

- *Ground Penetrating Radar Systems:* Ground penetrating radar systems (GPRs) are used for the purpose of detecting or obtaining the images of buried objects. GPRs must be operated below 960 MHz or in the frequency band 3.1-10.6 GHz. Operation is restricted to law enforcement, fire and rescue, scientific research institutions, mining companies, and construction companies.

- *Wall Imaging Systems:* Such systems are designed to detect the location of objects contained within a "wall", such as a concrete structure, the side of a bridge, or the wall of a mine. All wall imaging systems must be operated below 960 MHz or in the frequency band 3.1-10.6 GHz. Operation is restricted to law enforcement, fire and rescue, scientific research institutions, mining companies, and construction companies.

- *Through-wall Imaging Systems:* Such systems detect the location or movement of persons or objects that are located on the other side of a structure such as a wall. All through-wall imaging systems must be operated below 960 MHz or in the frequency band 1.99-10.6 GHz. Operation is restricted to law enforcement and fire and rescue.

- *Medical Systems:* Such systems are used for a variety of health applications to see inside the body of a person or animal. These systems must operate in the frequency band 3.1-10.6 GHz. Operation must be at the direction of, or under the supervision of, licensed health care practitioner.

- *Surveillance Systems:* Such systems are used as security fences by establishing a stationary RF parameter field and detecting the intrusion of persons or objects in that field. Technically these devices are not imaging systems, but for regulatory purposes they will be treated the same way as through-wall imaging and will be permitted to operate in the frequency band 1.99-10.6 GHz. Operation is restricted to law enforcement, fire and rescue organizations, public utilities, and industrial entities.

Vehicular Radar Systems

These devices are able to detect the location and movement of objects near a vehicle, enabling features such as near collision avoidance, improved airbag activation, and suspension systems that better respond to road conditions. The devices should operate in the 24 GHz band using directional antennas on terrestrial transportation vehicles provided the center frequency of the emission and the frequency at which the highest radiated emission occurs are greater than 24.075 GHz.

Communications and Measurement Systems

These include a wide variety of other UWB devices, such as high-speed home and business networking devices as well as storage tank measurement devices under Part 15 of the FCC's rules

subject to certain frequency and power limitations. These devices must operate in the frequency band 3.1-10.6 GHz. Equipment must be designed to ensure that operation can only occur indoors or it must consist of hand-held devices that may be employed for such activities as peer-to-peer operation. A number of industrial companies have demonstrated the feasibility of short-range, peer-to-peer UWB communications for applications in wireless local and personal area networks.

4 Potential Advantages and Limitations of UWB

In order to summarize the previous discussions and set the stage for a functional comparison between standard spread spectrum technologies with UWB, we list out some of the claimed advantages and potential limitations of UWB communications below.

Advantages

- ***Robust covert communication:*** In military communications, although sophisticated encryption techniques can prevent adversaries from decoding sensitive wireless transmissions, detectability of the signal compromises the location of the transmitter. Because of the very large spreading factor, UWB signals, with their noise-like spectra, are usually far hidden below the noise floor. Hence UWB systems offer a solution to the low probability of detection (LPD) requirement of military communication systems. In addition, the very large spreading factor also makes UWB signals resistant to jamming and interference from other radio systems.

- ***Ground/wall penetration:*** Since the UWB signal generated by an impulse radio system that operates in the lower frequency bands contains significant low frequency components, the UWB signal has a good chance of penetrating materials that are normally more opaque to higher frequencies.

- ***Accurate positioning:*** Since the transmission bandwidth of an UWB signal is in the gigahertz range, multipaths are resolvable down to path differential delays on the order of a nanosecond or less, i.e., down to path differential delays on the order of a foot or less. The capability to highly resolve multipaths (even in indoor environments) combined with the ability to penetrate through materials makes UWB suitable for accurate positioning applications.

- ***Robustness against multipath fading:*** Propagation measurements of UWB signals in typical indoor environments reveal that the fading margins required for reliable communications are considerably less than those required in narrow-band systems. This indicates the potential of UWB communication systems for robust indoor operation at low transmitted power levels.

- ***Multiple-access capability:*** Like any spread spectrum technique, UWB can provide multiple access capability. Due to the very large spreading gain of UWB systems, it is conceivable that a large number of users can be accommodated in a typical UWB system.

- ***Low-cost VSLI implementation:*** Since an UWB radio operates at baseband, no RF modulators and demodulators are needed in the transmitter and receiver design. The absence of RF and IF stages and the required filters and linear amplifiers, which are usually present in narrowband systems, reduces the complexity of an UWB radio. The use of the power amplifier can also be avoided if the transmission range is small (say in an indoor environment). This greatly simplifies the complexity and reduces the cost of the VLSI implementation of an UWB radio, as most of the space, power and cost is consumed by these components in a typical wireless radio. Moreover, the technology to transmit and receive UWB pulses is relatively low in complexity and could be inexpensively implemented compared to conventional spread spectrum systems. It is therefore possible to produce single-chip implementations of transceivers employing UWB with very few off-chip parts.

Potential Limitations

- ***Wide-band antenna design:*** The antennas employed in UWB systems are required to efficiently radiate EM signals over gigahertz of bandwidth. Design of such antennas is not a simple task. Although the design of wideband antennas has been a much researched topic in the radar community, efficient wideband antennas are usually bulky and may not be applicable in communication applications.

- ***Short-range transmission***: Without a power amplifier, the transmission range of an UWB radio is very limited. Although it has been claimed that medium-range (up to about 10 miles) communications using low-power UWB signals is possible, the design of small-size, efficient wideband power amplifiers and directional antennas is still not well known.

- ***Acquisition difficulty:*** With low transmission power and a highly spread bandwidth, acquisition of an UWB signal is difficult. In a packet network, a long preamble needs to be added to the beginning of each packet for the receiver to acquire the packet. The use of long preambles reduces the throughput of the network, and the detrimental effect of long preambles multiplies when multiple hops are traversed to relay information from the source to the destination.

- ***Interference to existing systems:*** Although it has been established that the interference of an UWB transmitter to most existing systems is minimal, a large aggregation of UWB transmissions could still pose a threat to critical systems like the GPS. In addition, the potential interference could be significant if higher power UWB signals are used for longer range transmission.

5 Functional Comparison of TM-UWB and SS

Traditional SS and TM-UWB systems employ not only different bandwidths, but they are also based on different design approaches. To provide a meaningful comparison between the TM-UWB and SS techniques, we adopt a functional comparison approach. First, a number of different application scenarios that are of the interest of the Air Force are considered. Then,

performance metrics pertaining to these application scenarios are employed to compare the two different types of signaling techniques.

We consider the following three different application scenarios, which require a wide range of capabilities of the supporting communication systems:

- ***Cooperative attack weaponry system:*** In this application, several units of ordnance (bombs, missiles, etc.) communicate with each other to exchange target and attack information. The number of ordnances is small and they can be tens of kilometers away from each other. They are traveling at high speed. This system represents the scenario in which a medium/long-range, low-rate communication system is needed among a few nodes with high mobility.

- ***Aerial surveillance system:*** In this application, a number of small aerial vehicles survey an area of about 10x10 sq. kilometers. The vehicles are moving at a relatively low speed and are transmitting imagery and control information among themselves. This system represents the scenario in which a medium-range, bursty high-rate communication system is needed among a medium number of nodes with medium mobility.

- ***Buried facility probing system:*** In this application, a large number of small sensors enter a buried facility to map out the situation inside the facility and relay information back to a collecting agent. This represents the scenarios in which a short-range, high-rate communication system is needed among a large number of nodes. The communication signals may also need to have the capability of penetrating dense materials, such as earth and walls. In addition, low power consumption is also an important constraint in the design of this system.

The TM-UWB and traditional SS signaling are compared based on their relative merits in the three scenarios above. In particular, the following performance metrics, which summarize the various required communication capabilities in these application scenarios, are used as the basis for comparison.

Performance metrics

- ***Transmission range:*** Traditional SS technologies, such as direct sequence and frequency hopping, are well proven for short, medium, and long range communications with proper choices of bandwidth and carrier frequency. Standards such as Bluetooth, IEEE 802.11b and IS-95 employ spread spectrum technology. For UWB, most of the current research and commercial activities are on short-range WPAN applications [4, 17]. A number of experimental and research studies have validated the suitability of UWB for short-range applications. For medium and long range communications, wideband power amplifiers are needed to raise the transmission power to higher levels. Currently available wideband power amplifiers are often inefficient and bulky. Although there have been claims that medium-range (up to about 10 miles) communications using low-power UWB signals is possible [18], the suitability of UWB for medium and long range communication applications needs further research.

- ***Data rate:*** It is also well established that SS can provide data rates up to tens of Mbps in short-range systems and from tens of kbps to about 1 Mbps in medium-range systems [13]. Because of the use of a much wider bandwidth, UWB has the potential of providing a much higher data rate. For instance, there have been experimental UWB systems that can provide data rates of hundreds of Mbps in a short range [18]. For medium-range communications, the advantage of UWB over traditional SS techniques may not be so clear since the receiver may need to collect more energy from a larger number of pulses to compensate for the low transmission power. This may reduce the achievable data rate of the UWB system.

- ***Interference issues:*** First we consider interference to other systems. Since most SS systems work in defined frequency bands, interference to other systems can be controlled easily through the specification of a proper out-of-band emission limit. For UWB systems, limitations have to be imposed on the power spectrum of the transmitted signal over the whole transmission band. It has been verified that the interference caused by the transmissions from a few UWB radios to other systems is negligible under the current FCC-imposed power limit [14, 18]. However, the aggregated transmission from a large number of low-power UWB radios and higher power transmission of medium-range UWB radios could still be a problem. In terms of interference and jammer rejection, UWB should be better than the SS counterpart, which has a much smaller spreading gain.

- ***Multiple access capability:*** With a much larger spreading factor, it is reasonable that an UWB system can support more users than a traditional SS system that uses a smaller bandwidth. However, the advantage is not as solid as one would think. The reason is that the multiple-access capability is reduced by interference from other communication systems that lie within the wide extent of the UWB signal band. This problem can be partially solved by notch-filtering out the narrowband interference at the expense of increasing the complexity of the UWB receiver.

- ***Covert communications:*** The very high spreading factor of an UWB system produces a noise-like spectrum that is typically well below the noise floor for most of the currently proposed applications. It is believed that the LPD performance of UWB is superior to that of a traditional SS system.

- ***Suitable channels:*** Because of its larger bandwidth, an UWB system has a finer multipath resolution than a traditional SS system. With a proper receiver design (e.g. a RAKE receiver), the UWB system is likely to be more robust in dense multipath environments [9, 10]. In addition, UWB signals generally have a better wall-penetrating ability than carrier-based SS signals. The wider bandwidth of an UWB signal may make it less susceptible to fast fading caused by Doppler spread in high mobility systems.

- ***Implementation complexity:*** The carrierless nature of an UWB system eliminates the need of the RF and IF stages and the required filters and linear amplifiers. Thus, it is easier to produce single-chip implementations of transceivers employing UWB with very few off-chip parts. In short-range systems, the use of the power amplifier can also be avoided. This further simplifies the complexity and reduces the cost of the VLSI implementation of an UWB radio. However, to support medium-range communications, wideband power amplifiers and other

off-chip components may need to be included. Thus, the implementation advantage of UWB is not as obvious as in a short-range system.

Relating back to the three application scenarios described above, the qualitative comparison between UWB and SS indicates a strong potential advantage in using UWB in the buried facility probing system; this particular application requires a short-range, high-rate, low-power, wall-penetrating communication system among a large number of nodes, which are requirements that UWB can meet well. For the other two scenarios of medium and long-range communications, the advantage of using UWB, whether presents at all, is not clear and needs to be further investigated.

6 Experimental Results

The goal of this part of the project is to provide experimental verification of the qualitative comparison between SS and UWB presented in the previous section. All experiments will be carried out employing the UWB radio equipment described in Section 6.1.

6.1 UWB Radio Equipment

The platform on which all of the ultra wideband tests were performed was Time Domain's PulsON 200 UWB evaluation kit. The PulsOn 200 evaluation kit is a flexible platform that allows the user to develop many solutions rather than a single solution (shown below in Figure 13). This kit includes hardware, antennas, and embedded software.

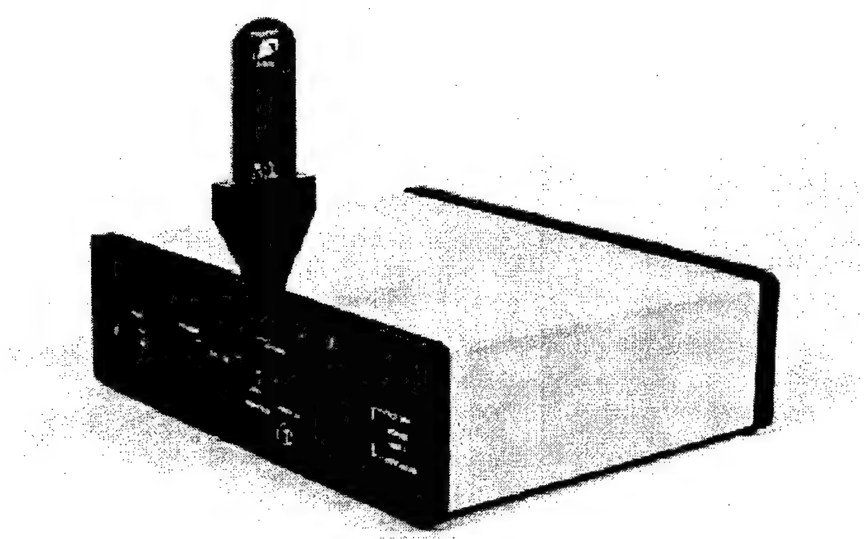

Figure 13: PulsON 200 Evaluation Kit

The PulsON 200 radio consists of a RF module and a development module (See Figure 14). The RF module contains a pulser/flipper that generates the UWB Gaussian monocycle pulse and changes the polarity of this pulse. It also contains a transmit/receive switch and an input low noise amplifier and filter. The development module contains the baseband processor which processes the correlated received data. It also forms input data into a optimized UWB packet

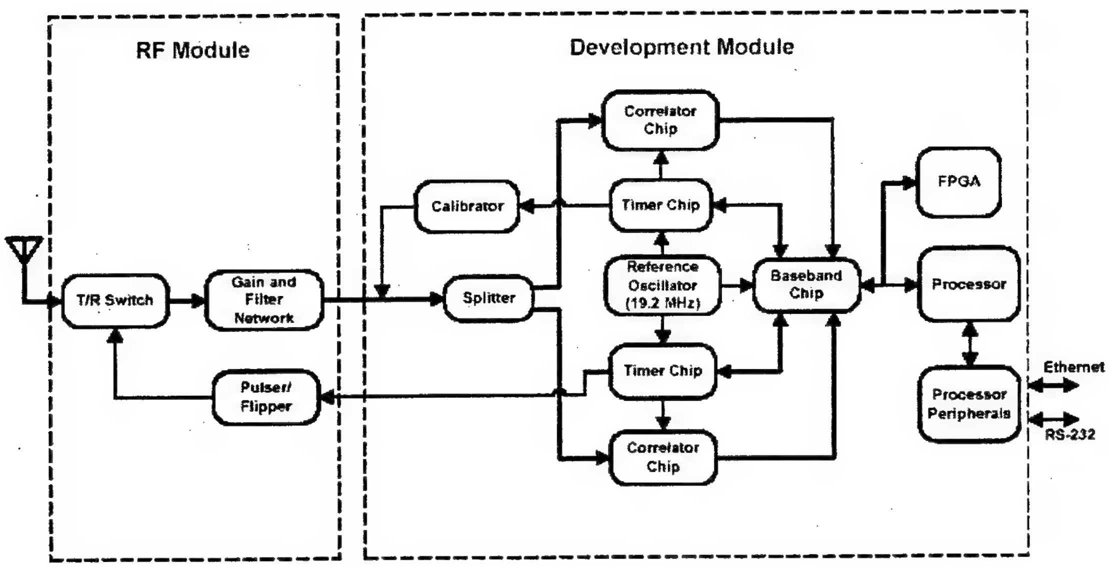

Figure 14: Block Diagram on PulsON 200 Evaluation Kit

These radios have a power output of 50μW and have a transmission bandwidth from 3.1 to 10 GHz. The PulsON 200 evaluation kits are designed per FCC specifications. The first sets of measurements were taken using the evaluation kits in their factory configured state. The radios were set up in a simplex mode with one radio set as a transmitter and the other as a receiver. This setup is illustrated below in Figure 15.

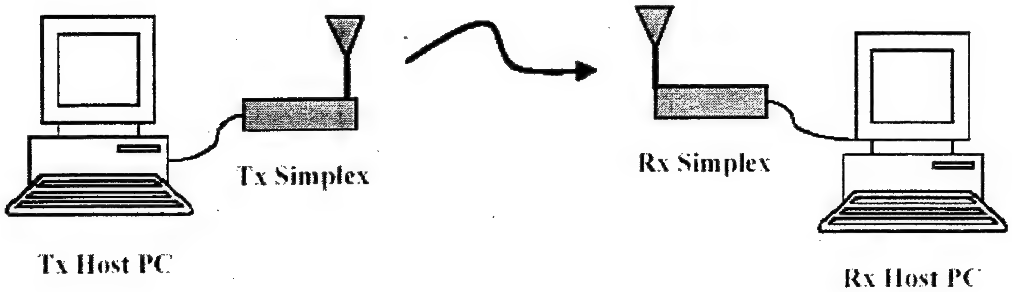

Figure 15: Simplex Setup of PulsON 200 Evaluation Kit

There is a performance analysis tool (PAT) that acts as one of the host graphical user interfaces. The PAT allows the user to interface with and control the PulsON 200 radio and determine statistics of a simplex communications link such as bit error rate (BER), while changing parameters like acquisition period length, data rate, etc (see Figure 16). Using the PAT that is packaged with the evaluation kit, one radio was set up as a transmitter and the other one as a receiver.

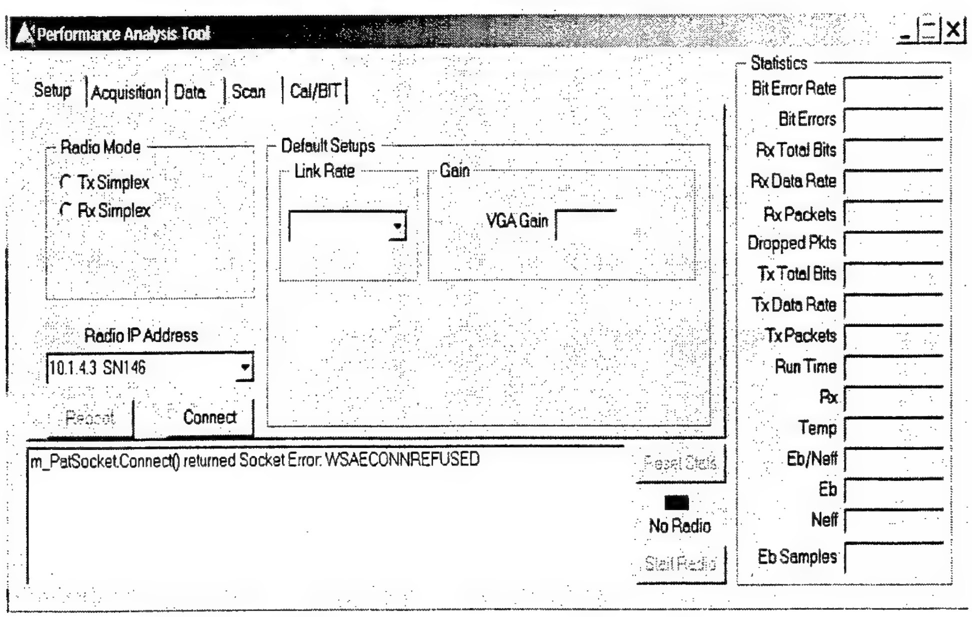

Figure 16: Performance Analysis Tool GUI

6.2 TM-UWB Experiments

Measurements were taken for a representative set of communication parameters. Two sets of measurements were conducted outdoors and one set of measurements was conducted indoors. For the outdoor measurements, it was simple to vary the distance between the transmitter and the receiver, with transmitter and receiver at a height of three feet off the ground. At each distance, statistical data was gathered for each given data rate starting at 150 kbps up to 9.6 Mbps. Also, received waveforms were captured for the data rates of 150 kbps, 300 kbps, and 600 kbps for each distance. Measurements were taken with and without the use of the ZVE-8G external wideband power amplifier. The output of the radio was attenuated by 10 dB so as to not saturate the input of the amplifier. For the indoor measurements, the performance was investigated for four different representative communication scenarios involving different distances and locations with respect to walls. Statistical data was gathered for data rates between 150 kbps and 9.6 Mbps. The external power amplifier was not tested for the indoor scenario. The measured data is tabulated in the Appendix.

The second set of measurements were taken with the same setup except the power outputs of the radios were amplified. The output power was amplified using the mini-circuits ZVE-8G wideband amplifier. The output of the radio had to be attenuated so as to not saturate the input of the amplifier. Thus, the output power was -12.2 dBm –10 dBm +30 dBm = +8.8 dBm.

In the following subsections, we present some performance results collected from the raw data tabulated in the Appendix. For the outdoor scenarios, the results show the performance effects of varying the distance on the achieved data rate, the bit error rate, and the effective bit energy-to-noise density ratio, E_b/N_{eff}. In addition, we plot the bit error rate as a function of E_b/N_{eff} for each of the outdoor scenarios.

6.2.1 Outdoor environment with no external power amplifier

Figure 17 below shows how the effective bit energy-to-noise density ratio, E_b/N_{eff}, varies as a function of the distance between the transmitter and receiver. The results represent measurements taken at four different transmission data rates for two sets of experiments conducted on different days. We observe that E_b/N_{eff} decreases as the distance increases, as expected. It is difficult to deduce the path loss exponent from the value of E_b/N_{eff} since the definition of the effective noise power spectral density, N_{eff}, entails many channel, antenna, and circuitry effects. However, applying a curve fitting algorithm to the data from experiment 1 yielded path loss exponents of 1.5 (R=0.905), 2.17 (R=0.862), and 2.29 (R=0.992) for transmission data rates of 150 kbps, 1.2 Mbps, and 9.6 Mbps, respectively. Thus, a path loss exponent of approximately 2 is a reasonably good fit for the measurements taken in the outdoor environment for distances under 200 feet.

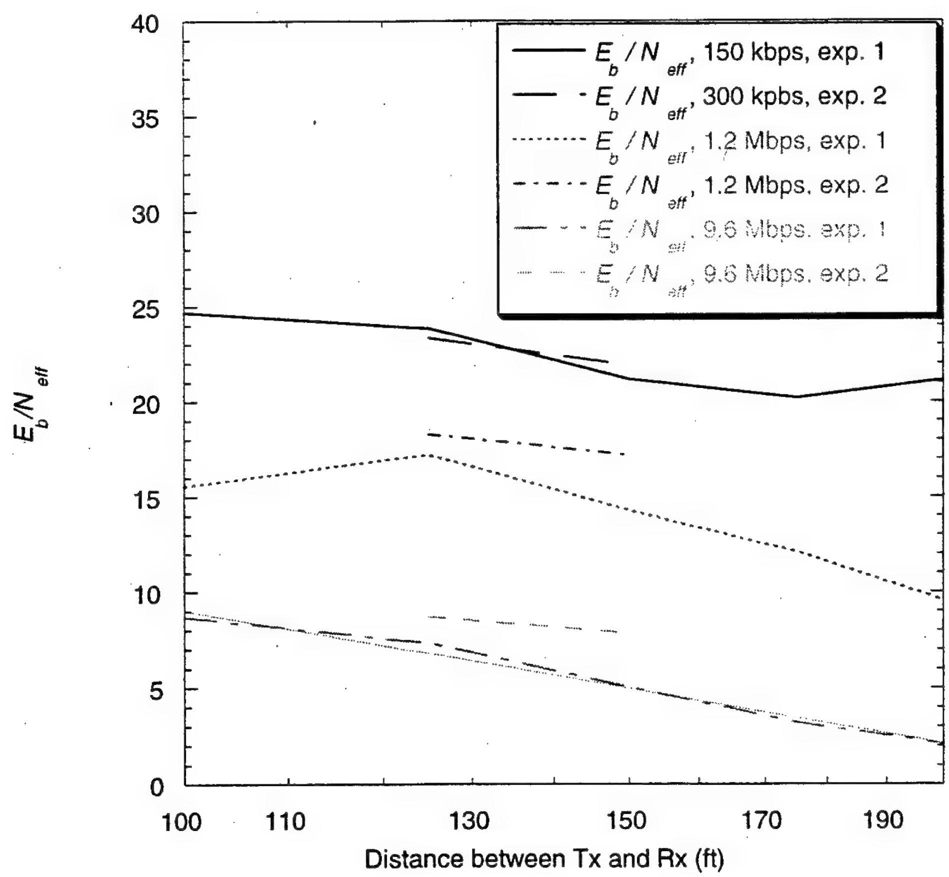

Figure 17: Received E_b/N_{eff} as a function of distance between transmitter and receiver, outdoor radio channel with no external power amplifier.

The bit error rates (BERs) obtained at different data rates are plotted in Figure 18. We note that we observed no bit errors in the 100 million bits that we transmitted in the case of the 150 kbps data rate, except for the extreme case of 200 ft distance. The results for experiment 1 show, as expected, that the BER increases as the distance increases, showing the same trend as E_b/N_{eff} varies according to distance. However, the results for experiment 2 show approximately the same BER at both distances at which data was measured. This can be attributed to the fact that the expected difference in path loss between the two sets of measurements was only 1.4 dB. Thus, even small variations in the multipath environment could account for these results.

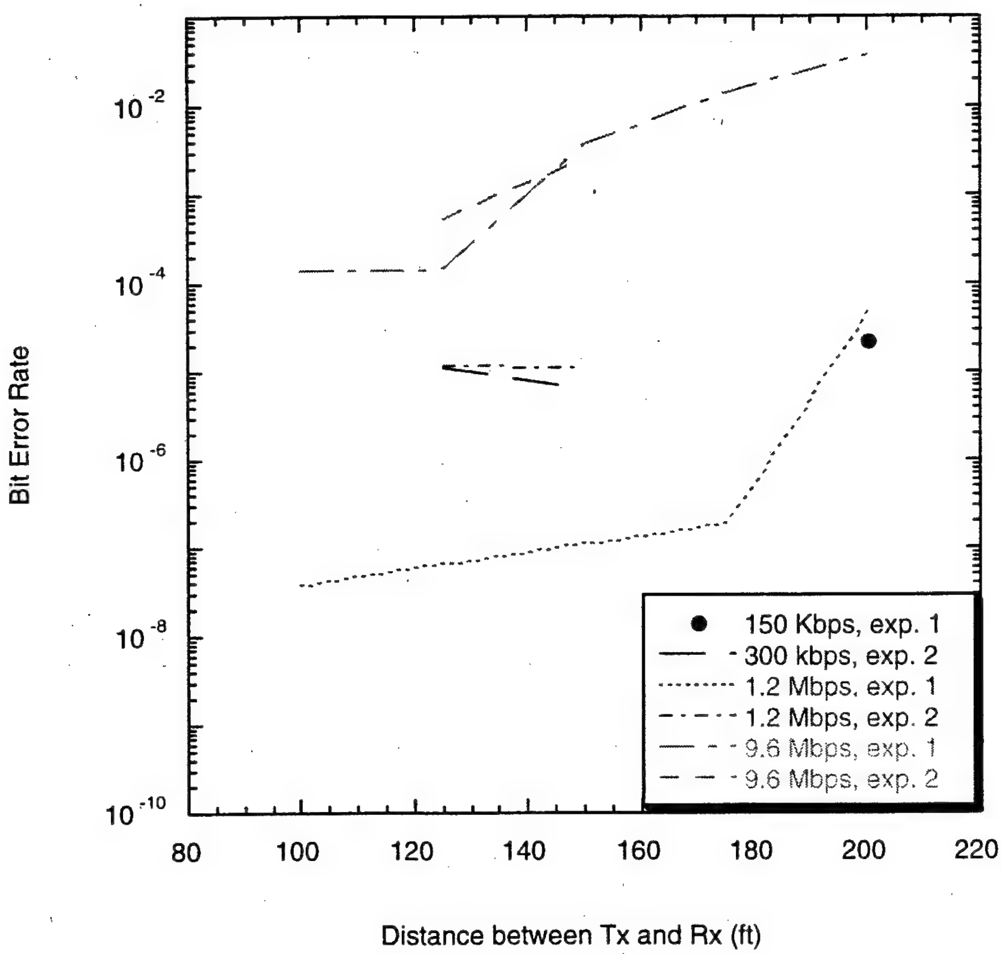

Figure 18: Bit error rate as a function of distance between transmitter and receiver, outdoor radio channel with no external power amplifier.

Figure 19 shows the plot of BER versus E_b/N_{eff}. We observe that the results from experiment 1, as well as the results from experiment 2 at 9.6 Mbps, match with the performance expected from theory. However, the results from experiment 2 at 300 kbps and 1.2 Mbps differ significantly from the expected results. The results from experiment 2 are averaged over more locations than the results from experiment 1, and thus we expect that the difference in performance is caused by degradation from severe multipath at some locations.

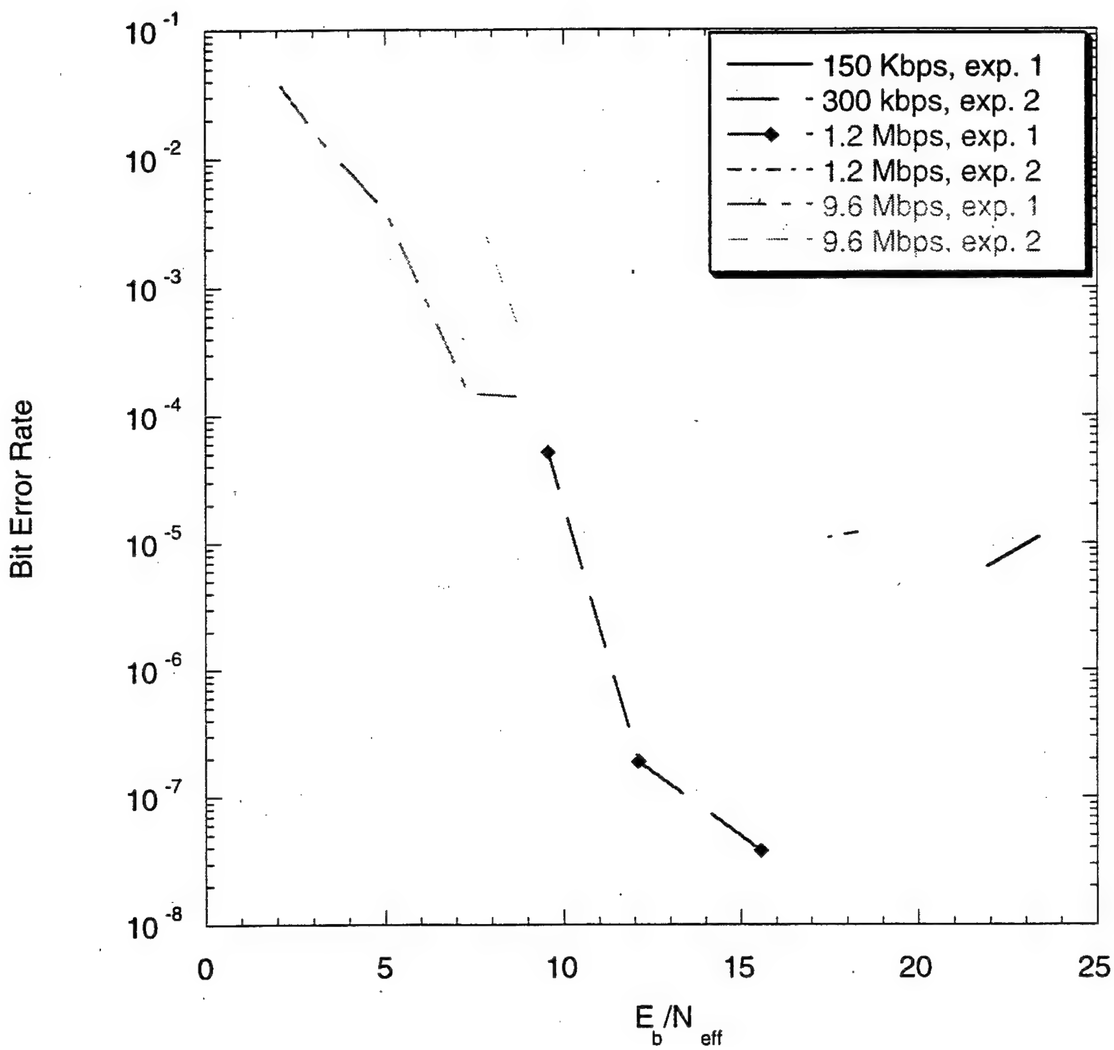

Figure 19: Bit error rate as a function of Eb/Neff, outdoor radio channel with no external power amplifier.

Finally, the throughput of the link obtained at different data rates are plotted in Figure 20 as a function of the distance. Again, we see the throughput drops as the distance increases.

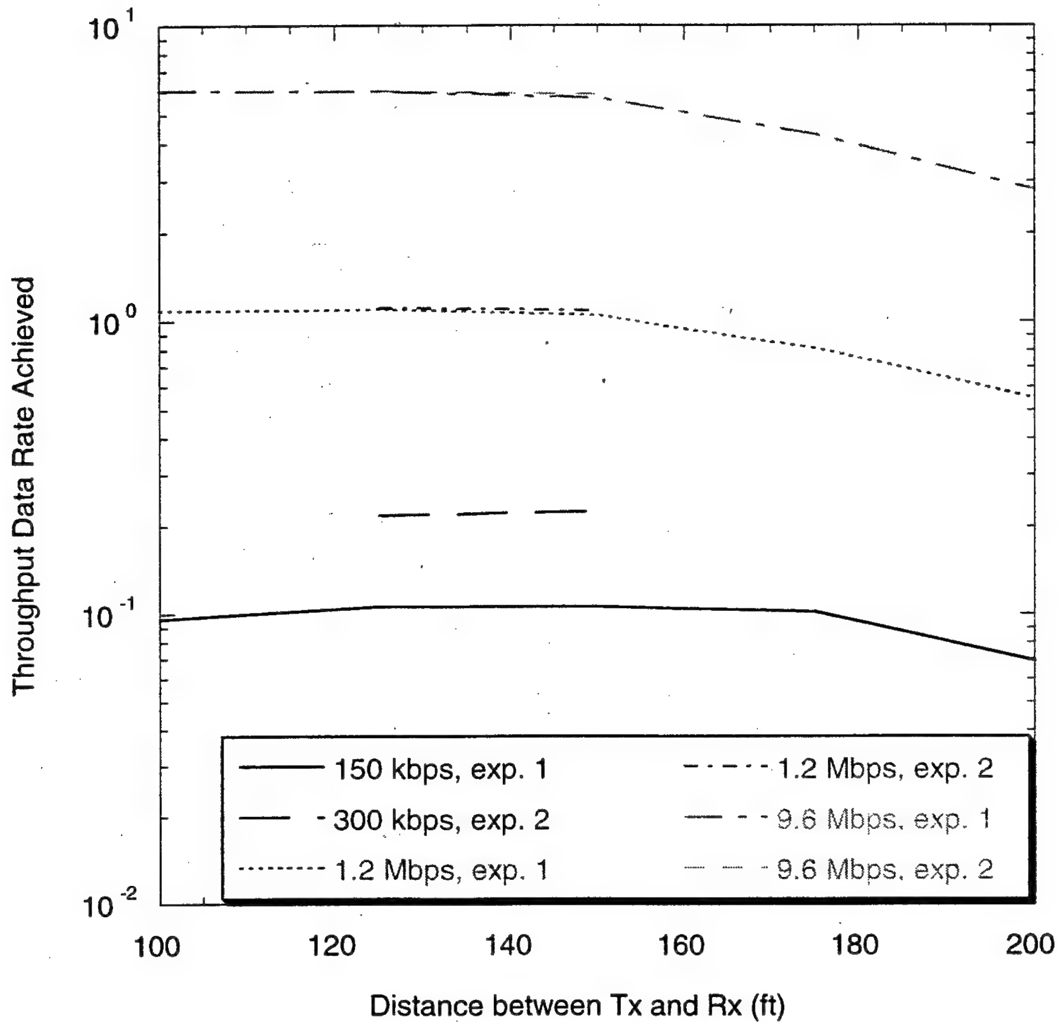

Figure 20: Data rate achieved (throughput) as a function of distance between transmitter and receiver, outdoor radio channel with no external power amplifier.

A significant problem that occurred in this and the following experimental scenarios is the unreasonable number of dropped (non-acquired) and received packets that were reported. That is, the number of dropped packets was a non-monotonic function of the transmission rate. Extremely high dropping rates were seen at low data rates; for instance, the dropping rate was approximately 25.6% for the 150 kbps transmissions at 100 feet. On the other hand, the dropping rate was extremely small for some high data rates; for example, at 9.6 Mbps and 100 feet, the dropping rate was 0.0051%. It is not clear whether these results reflect a problem in the radio or a problem in the PAT. Our intuition is that the problem is with the PAT.

Some information can be gleaned from the dropped packet information. For example, by 200 feet, the dropping rate across all data rates approaches 50%.

Summarizing the results from this experiment, we conclude that the maximum range of 200ft is not supported at the transmitted output power level of –12.2 dBm because of dropped packets. However, the maximum data rate of 9.6 Mbps seems to provide good performance at 150 feet.

6.2.2 Outdoor environment with external power amplifier

Figure 21 below shows how the effective bit energy-to-noise density ratio, E_b/N_{eff}, varies as a function of the distance between the transmitter and receiver. We observe that E_b/N_{eff} decreases as the distance increases, as expected. Again, it is difficult to deduce the path loss exponent from the value of E_b/N_{eff} since the definition of the effective noise power spectral density N_{eff} entails many channel, antenna, and circuitry effects. Applying the curve-fitting technique used in the previous section for the exponential path-loss model, the path loss exponent is found to be 3.86 (R=0.99), 3.79 (R=0.996), and 3.89 (R=0.996) for transmission rates of 150 kbps, 1.2 Mbps, and 9.6 Mbps, respectively. Thus, at these increased transmission distances, the path loss exponent is found to be close to 4.

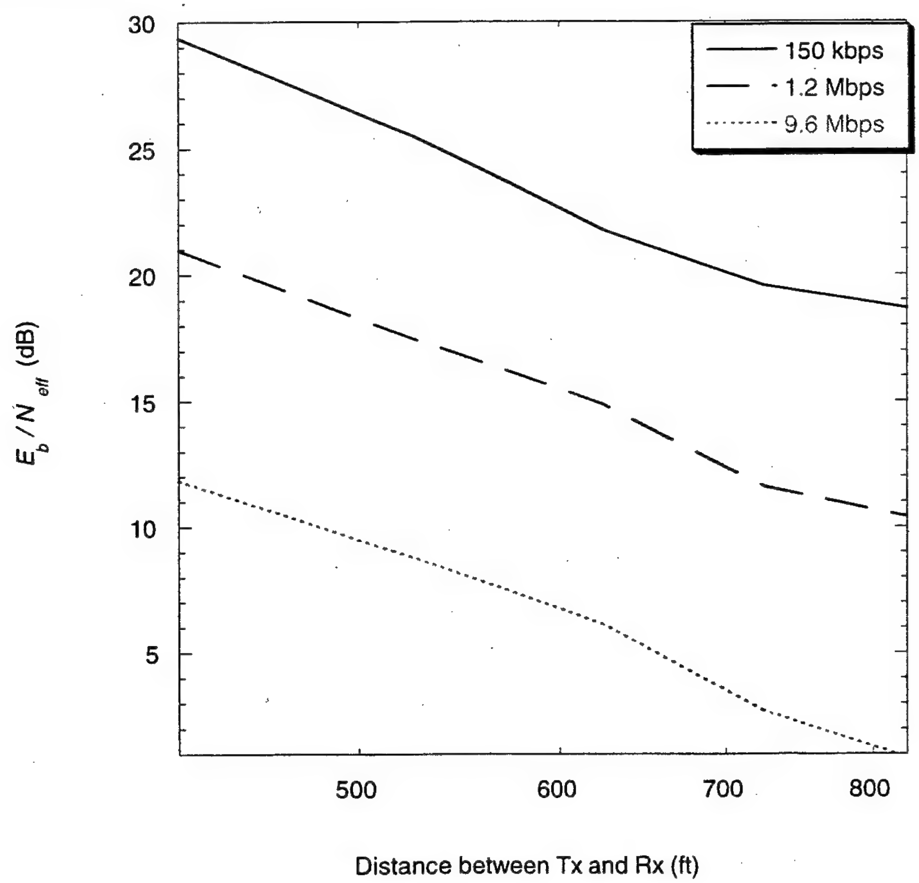

Figure 21: Received E_b/N_{eff} as a function of distance between transmitter and receiver, outdoor radio channel with external power amplifier.

The bit error rates (BER) obtained at different data rates are plotted in Figure 22. As expected, the BER increases as the distance increases, showing the same trend as E_b/N_{eff} varies according to distance.

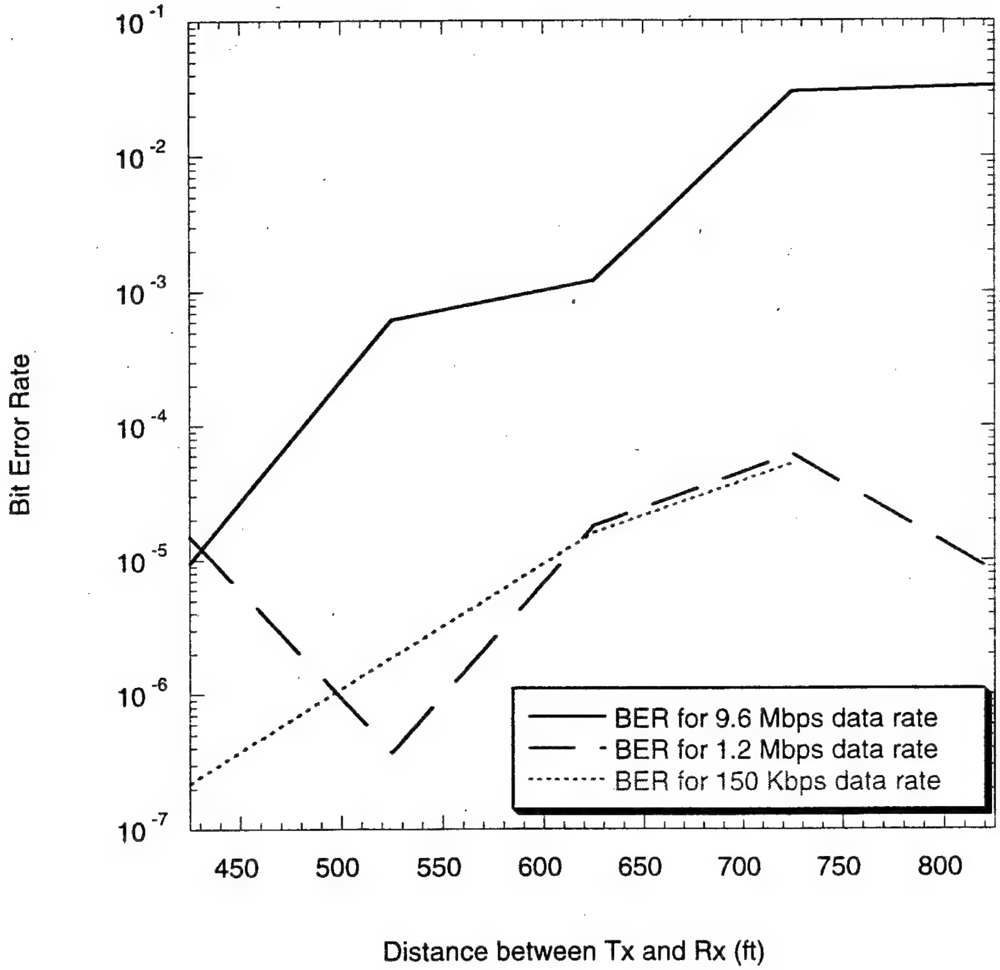

Figure 22: Bit error rate as a function of distance between transmitter and receiver, outdoor radio channel with external power amplifier.

The throughput of the link obtained at different data rates are plotted in Figure 23 as a function of the distance. Again, we see that the throughput drops as the distance increases.

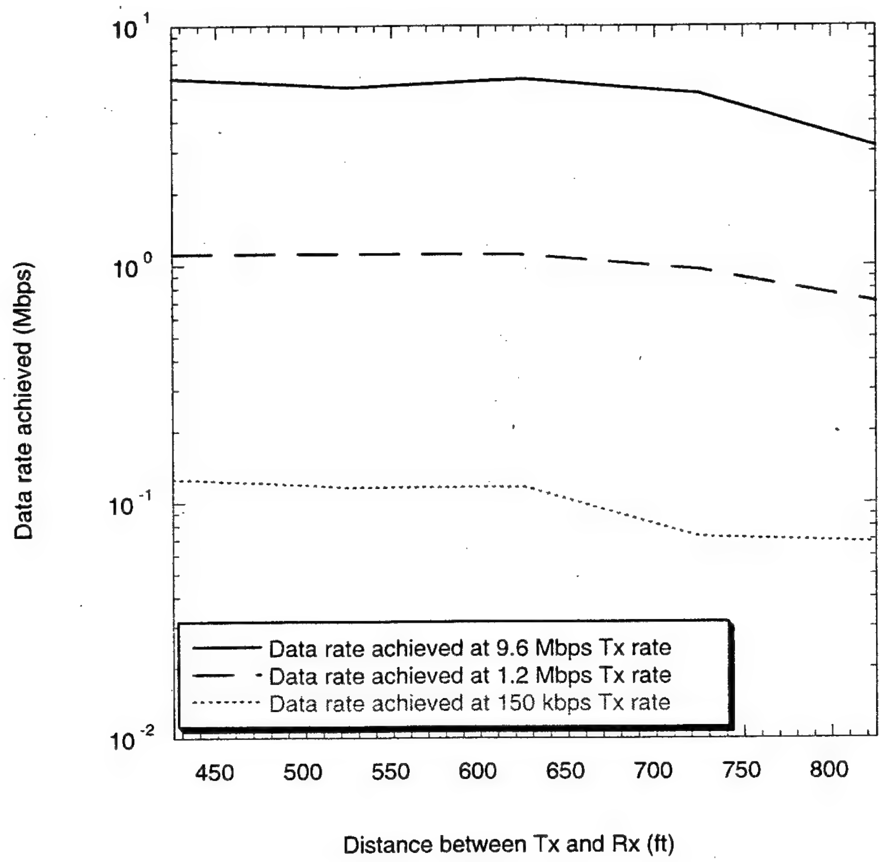

Figure 23: Data rate achieved (throughput) as a function of distance between transmitter and receiver, outdoor radio channel with external power amplifier.

The results on acquisition (dropped packets) are similar to the results without the external power amplifier. The dropping rate is again a non-monotonic function of the transmission rate. However, at 825 feet, the dropping rate exceeds 0.5 for all transmission rates. At 725 feet, the dropping rate is approximately 13% to 14% for data rates from 600 kbps to 4.8 Mbps. This may be acceptable for some applications, although dropping rates less than 1% are generally desirable for most networking scenarios. Note that for the higher data rates of 4.8Mbps and 9.6Mbps at 825 feet, the BER is close to or exceeds 10^{-2} for those packets that are acquired, thus rendering the use of those data rates questionable even if longer preambles and acquisition periods are employed.

Summarizing the results from this experiment, we conclude that at the medium data rates of 1.2 Mbps, a maximum range of approximately 725 ft can be supported at the transmitted output power level of 8.8 dBm. At the longer range of 825 ft, the acquisition performance seems to be bad enough to limit the usefulness for most scenarios.

6.2.3 Indoor environment with no external power amplifier

We also carried out an experiment in an indoor environment. The layout of the test site is shown below in Figure 24, where the bold lines indicate exterior walls and thin lines denotes interior walls.

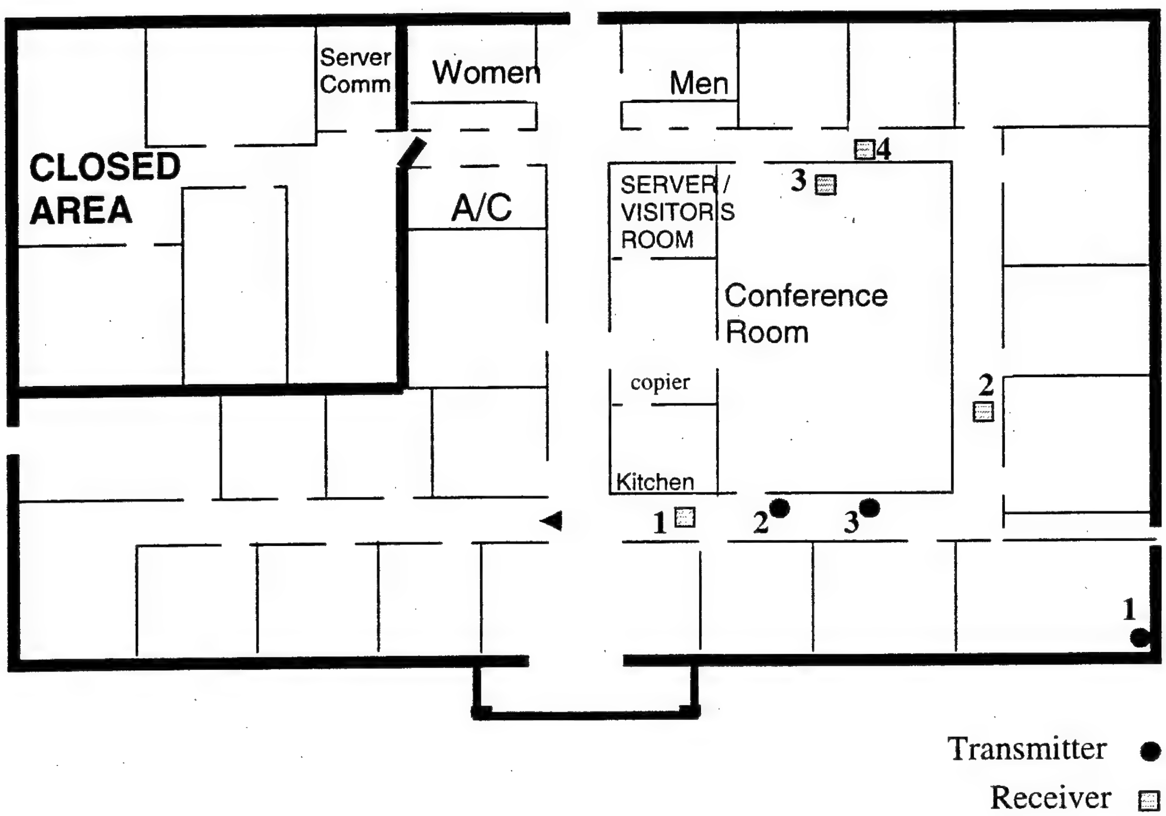

Figure 24: Indoor Test Layout

The throughput and BER performance for different locations of the transmitters and receivers are shown in Figures 25 and 26, respectively. As shown in the figures, the UWB transmission is rather robust in the indoor environment at various data rates. The presence of multipath fading does not seem to have a significant detrimental effect on the UWB transmission even at the low transmission power of –12.2 dBm.

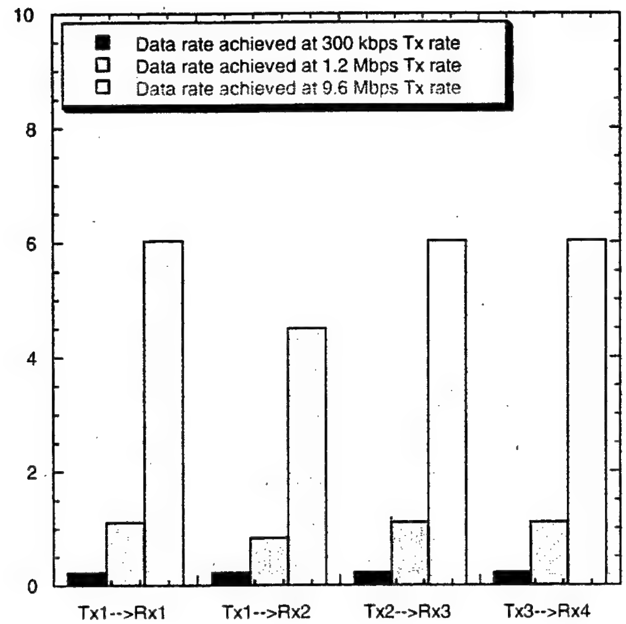

Figure 25: Data rates achieved for various indoor transmission scenarios and transmission rates.

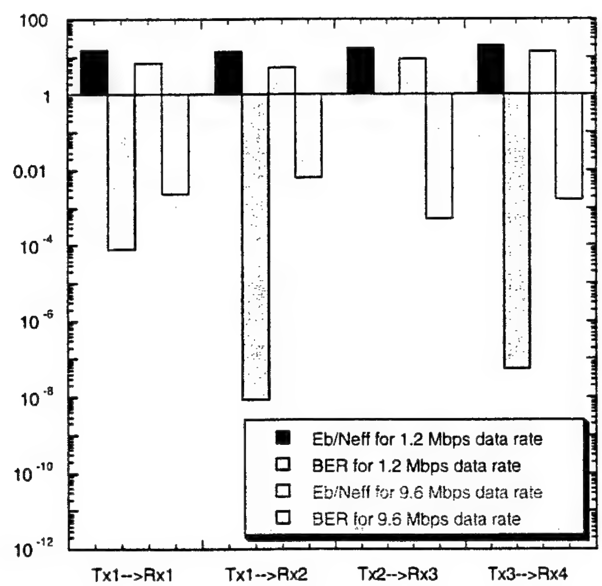

Figure 26: E_b/Neff and bit error rates for various indoor transmission scenarios and transmission rates.

Acquisition results were more reasonable in the indoor environment, although the dropping rate was still not a monotonic function of the data rate or constant over different transmission rates. Only one transmission scenario showed a significant number of dropped packets, which was the scenario with the transmitter in position Tx1 and the receiver in position Rx2, which showed a dropping rate of approximately 25% for all transmission rates over 150 kbps.

Overall, the results for indoor transmission indicate that high data rates can be achieved at most of the indoor locations with acceptable acquisition and bit error probabilities.

6.3 Benchmark Comparison

The main objective of this part of experimental research effort is to provide a reasonably fair comparison between employing UWB and SS in the three application scenarios described in Section 5. A very wide variety of commercial and military communication systems that employ SS signaling are specifically designed for different applications. It is impossible to compare UWB to all of these SS systems. Here we adopt a *benchmarking* approach to perform the comparison of the SS and UWB technologies. A representative commercial[2] SS system is identified for each of the three application scenarios described in Section 5. The limitation on existing UWB equipment has restricted the maximum transmission range in the experiments conducted to 800 ft. This limits the comparison only to a short-range system with the actual experimental data. For medium and long range systems, we extrapolate the experimental results to the desired power level by the theoretical model of square-law path loss as verified by the experimental results.

Based upon a preliminary survey on commercial SS communication systems, the following representative SS systems are chosen as benchmarks for the three application scenarios described in Section 5:

- ***Cooperative attack weaponry scenario:*** The representative SS system chosen for this scenario is the frequency hop spread spectrum radio produced by FreeWave, Inc. This radio operates at the 900 MHz ISM band. The whole 900 MHz ISM band is divided into 7 bands and each band has a bandwidth of about 3.7 MHz. The spreading gain is 15 and the maximum data rate is about 144 kbps. The maximum output power is 30 dBm and a maximum line-of-sight range of 60 miles can be achieved. The experimental results of the UWB system do not suggest that this value of range can be achieved without the use of directional antennas with high directional gain.

- ***Aerial surveillance scenario:*** The representative SS system chosen for this scenario is the IEEE 802.11 wireless LAN system under outdoor operation. The system specification is essentially the same as the indoor system, except that the maximum transmission power increases to 30 dBm and omni-directional antennas with higher gains are employed. The

[2] Commercial SS systems are considered because their specifications are widely available in the public domain.

maximum range can be as large as 1 mile. A larger range can be achieved if directional antennas are employed. The UWB experimental results suggest that the UWB system can support the data rate of 1.2 Mbps at a range of 725 ft. The transmission power level of 8.8 dBm is needed to achieve this performance. For the rate of 9.6 Mbps, the transmission range drops to about 400 ft or below. Applying a path-loss exponent of 3.86, as suggested by the UWB experiment over longer transmission ranges with power amplification, the transmission range for even 1.2 Mbps is found to fall far short of a mile. The approximate transmission range is expected to be approximately 0.56 miles if the transmission power level of 30dBm were available. Extrapolating by the square-law path loss model, if 30dBm transmission power were available, the range of the UWB system would well exceed 1 mile. Thus, the performance will depend greatly on the propagation conditions. For the aerial surveillance scenario, it is expected that the path-loss exponent will be closer to 2, as there is less opportunity for multipath or shadowing to degrade the performance from free-space propagation. However, it is unclear what level of interference the UWB signal at the high transmission power level will cause to other existing systems.

- ***Buried facility probing scenario:*** The representative SS system chosen for this scenario is the IEEE 802.11 wireless LAN system under indoor operation. Two types of spreading techniques, namely DS and FH, are specified in the IEEE 802.11 standard. We will primarily focus on the DS system. This SS system operates at the 2.4 Ghz ISM band. The (spread) bandwidth is about 22 MHz and the spreading gain is about 10dB. The maximum data rate is 2 Mbps. If complementary coded keying (CCK) is employed (like in 802.11b), a maximum data rate of 11 Mbps can be obtained at the expense of the spreading gain. For most commercially available products, the transmission power is limited to 15dBm and a maximum range of 150 ft is common for indoor operation with an omni-directional antenna. Common experiences from users seem to indicate that practical range is significantly less than 150 ft. The UWB experimental results suggest that the UWB system can provide compatible range and data rate at a much lower power level at –12.2 dBm.

7 Conclusions and Further Work

We have presented a literature survey of the present state of research and applications of UWB communications. A literature repository has set up and is available at http://wireless.ece.ufl.edu/uwb/ (login: uwb, password: Afrl02). In summary, it is suggested in the literature that UWB provides advantages including more robust covert communication, ground/wall penetration, accurate positioning, robustness against multipath fading, better multiple-access capability, and low-cost VSLI implementations. However, UWB may suffer from difficulties in wide-band antenna design, short transmission range, long acquisition time, and interference to existing critical systems.

A functional comparison between UWB and traditional SS technologies based on published results in the open literature was conducted. Three hypothetical application scenarios that are of the interest of the Air Force were considered. A cooperative attack weaponry system, an aerial surveillance system, and a buried facility probing system were selected as the representative

scenarios since they require a wide range of capabilities of the supporting communication systems. UWB and traditional SS signaling techniques were compared based on their relative merits in these three scenarios. In particular, performance metrics, which summarize the various required communication capabilities in these application scenarios, were used as the basis for comparison. It was found that there is a strong potential advantage of using UWB in the buried facility probing system, for which a short-range, high-rate, low-power, wall-penetrating communication system is needed among a large number of nodes. Nevertheless, there are still many technical issues that need to be addressed before UWB can be effectively applied to these application scenarios. For instance, in a multihop network, the long acquisition time required for UWB may significantly reduce the throughput of the network. For the other two scenarios of medium and long range communications, the advantage of using UWB, whether present at all, was not clear and needs to be further investigated.

The transmission experiments employing the PulsON 200 evaluation kits from Time Domain, Inc. were conducted in order to verify the qualitative comparison between SS and UWB, which was obtained in the preliminary analysis during the first half of the project. The experimental results appear to collaborate with the literature review observations that UWB can provide data rate and range performance comparable to SS systems at lower transmission power level for short range (a few hundred feet) communication scenarios. A similar conclusion would be applicable to medium range (up to a mile) applications if significantly high transmission power (30 dBm) is available. While this required level of transmission power may be available in practice, the circuitry involved would possibly be bulky if fabricated with the current technologies. In addition, the transmission of a UWB signal at high power level may cause detrimental interference to other critical communication systems like GPS. Thus, the benefit of UWB for medium range communication applications is unclear and needs further investigation.

8 Appendix

8.1 Outdoor Test Results without Power Amplifier, Experiment 1

Output power: -12.2dB
Tx height: 31"
Rx height: 33"
Channel impulse response/PDP measured at 200 Kbps data rate

Table 1: Distance from Tx to Rx – 100 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped packets
150 Kbps	96.73Kbps	6.1e7	0.0	62.08	37.39	1858/ 640
300 Kbps	167.22Kbps	1.0e8	0.0	56.05	34.52	3064/ 1210
600 Kbps	567.86Kbps	3.7e8	0.0	50.12	30.82	11288/ 0
1.2 Mbps	1.09Mbps	7.1e8	3.8e-8	43.54	27.98	21647/ 96
2.4 Mbps	1.89Mbps	1.2e9	5.0e-4	34.40	30.97	35877/ 88
4.8 Mbps	3.71Mbps	2.5e9	7.1e-6	31.03	20.78	75512/ 3
9.6 Mbps	6.04Mbps	3.7e9	1.4e-4	26.43	17.75	111819/ 6

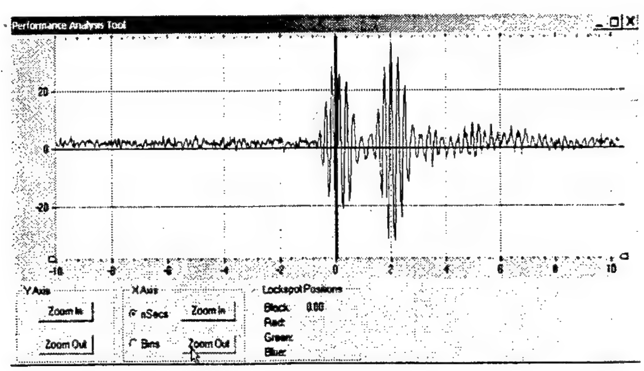

Figure 27. Received signal at 100 ft.

Table 2: Distance from Tx to Rx –125 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped packets
150 Kbps	106.35Kbps	6.9e7	0.0	62.70	38.86	2101/ 470
300 Kbps	187.82Kbps	1.2e8	1.5e-7	56.71	34.97	3722/ 902
600 Kbps	567.91Kbps	3.9e8	0.0	51.00	31.61	11791/ 0
1.2 Mbps	1.10Mbps	6.6e8	0.0	44.98	27.77	20240/ 0
2.4 Mbps	2.05Mbps	1.4e9	0.0	38.20	24.66	42718/ 1
4.8 Mbps	3.65Mbps	2.4e9	2.1e-7	32.62	21.60	73060/ 3
9.6 Mbps	5.97Mbps	3.9e9	1.5e-4	25.34	18.01	118700/ 7

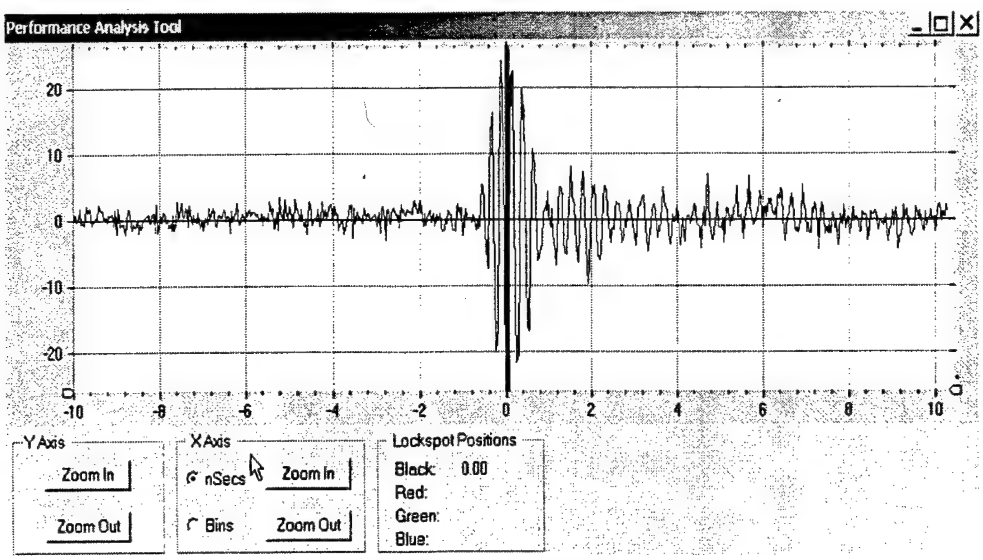

Figure 28. Received signal at 125 ft.

Table 3: Distance from Tx to Rx – 150 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
150 Kbps	105.56Kbps	7.1e7	0.0	59.35	38.19	2166/ 502
300 Kbps	191.86Kbps	1.3e8	0.0	53.34	34.31	3843/ 827
600 Kbps	540.89Kbps	3.5e8	0.0	47.26	31.08	10587/ 530
1.2 Mbps	1.05Mbps	7.2e8	0.0	41.57	27.29	21910/ 1039
2.4 Mbps	1.96Mbps	1.2e9	7.0e-007	35.22	24.04	37102/ 1885
4.8 Mbps	3.46Mbps	2.1e9	1.74e-004	29.26	21.66	63937/ 3487
9.6 Mbps	5.66Mbps	3.5e9	3.8e-003	22.89	17.85	105091/ 5666

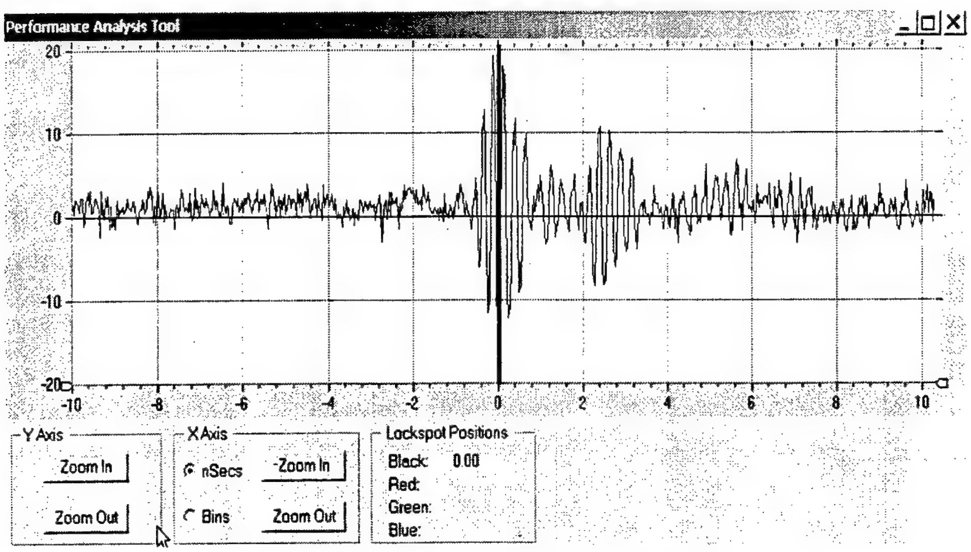

Figure 29. Received signal at 150 ft.

Table 4: Distance from Tx to Rx – 75 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Nef	Rx Packet/ Dropped Packets
150 Kbps	101.67Kbps	6.4e7	0.0	57.34	37.15	1959/ 589
300 Kbps	183.89Kbps	1.2e8	0.0	51.36	34.09	3661/ 1053
600 Kbps	419.98Kbps	2.7e8	0.0	45.27	30.19	8182/ 3084
1.2 Mbps	812.81Kbps	6.3e8	1.9e-7	39.22	27.11	19230/ 7197
2.4 Mbps	1.50Mbps	9.1e8	6.8e-5	32.85	24.61	27843/ 11000
4.8 Mbps	2.67Mbps	1.8e9	2.0e-3	27.06	20.93	54974/ 21404
9.6 Mbps	4.26Mbps	2.6e9	1.4e-002	20.77	17.56	78147/ 32623

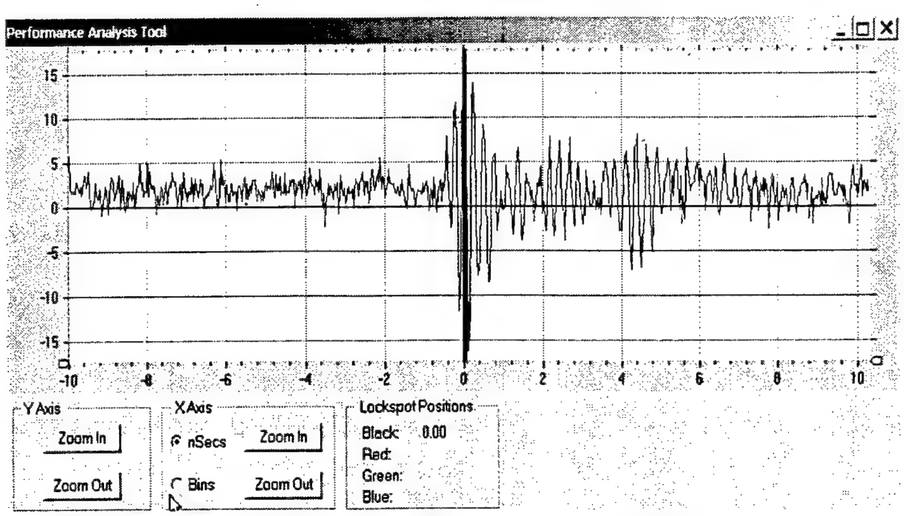

Figure 30. Received signal at 175 ft.

Table 5: Distance from Tx to Rx – 200 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
150 Kbps	68.79Kbps	4.2e7	2.2e-5	58.08	36.96	1271/ 1127
300 Kbps	103.77Kbps	6.7e7	4.3e-5	48.99	33.11	2050/ 2630
600 Kbps	288.20Kbps	1.8e8	1.5e-5	43.08	30.02	5518/ 5562
1.2 Mbps	548.49	3.4e8	5.1e-5	36.88	27.32	10234/ 10608
2.4 Mbps	1.04Mbps	6.4e8	1.3e-3	30.58	24.28	19659/ 19885
4.8 Mbps	1.85Mbps	1.1e9	1.0e-2	24.63	20.89	34396/ 34416
9.6 Mbps	2.80Mbps	8.6e8	3.7e-002	18.54	16.42	26203/ 38496

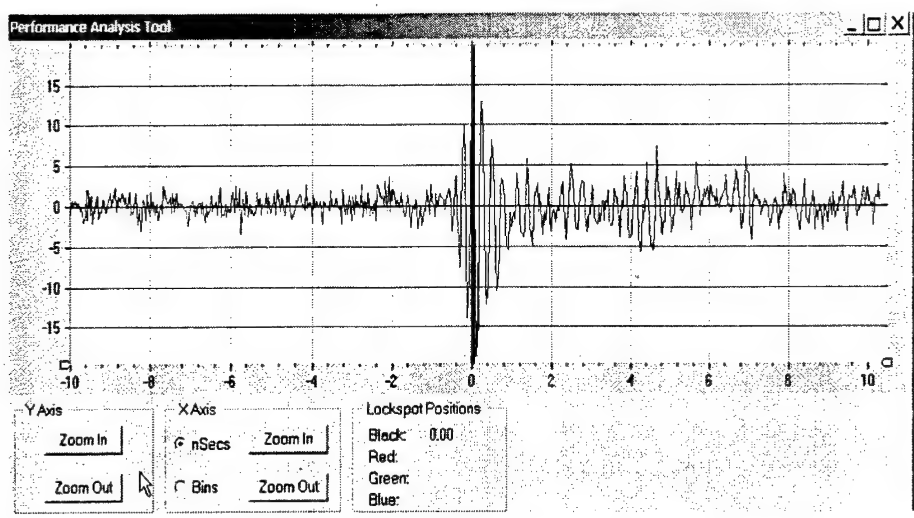

Figure 31. Received signal at 200 ft.

8.2 Outdoor Test Results without Power Amplifier, Experiment 1

Table 6: Distance – 125 ft

		Link Rate	Rx Data Rate	Rx Bits	BER	Eb	Neff
Position 1	1	300 Kbps	220.34 Kbps	153799200	4.70E-05	58.97	34.75
		1.2 Mbps	1.11 Mbps	782181600	4.40E-05	46.83	28.38
		9.6 Mbps	6.0 Mbps	4.28E+09	6.30E-04	28.27	18.93
Position 2	2	300 Kbps	219.36 Kbps	153110400	2.90E-05	58.73	34.4
		1.2 Mbps	1.11 Mbps	792677600	3.10E-05	46.74	28.78
		9.6 Mbps	5.99 Mbps	4.28E+09	6.40E-04	27.95	19.47
Position 3	3	300 Kbps	221.38 Kbps	150092800	1.20E-07	57.93	34.41
		1.2 Mbps	1.11 Mbps	792218400	7.90E-06	47.17	28.72
		9.6 Mbps	6.03 Mbps	4.32E+09	1.30E-03	27.24	19.22
Position 4	4	300 Kbps	222.85 Kbps	154881600	1.10E-06	58.95	35.94
		1.2 Mbps	1.12 Mbps	799926400	2.10E-06	46.48	28.42
		9.6 Mbps	6.04 Mbps	4.27E+09	3.80E-04	27.91	19.09
Position 5	5	300 Kbps	226.44 Kbps	157604000	5.10E-08	58.8	35.66
		1.2 Mbps	1.12 Mbps	780344800	3.10E-07	46.68	27.7
		9.6 Mbps	6.04 Mbps	4.40E+09	3.40E-04	28.39	18.91
Position 6	6	300 Kbps	226.02 Kbps	157308800	6.40E-09	58.98	35.48
		1.2 Mbps	1.12 Mbps	771685600	3.00E-08	46.74	27.88
		9.6 Mbps	6.04 Mbps	4.06E+09	2.50E-04	28.34	18.9
Position 7	7	300 Kbps	187.82 Kbps	122081600	1.50E-07	56.71	34.97
		1.2 Mbps	1.10 Mbps	663872000	0	44.98	27.77
		9.6 Mbps	5.97 Mbps	3.89E+09	1.50E-04	25.34	18.01

		Link Rate	Rx Packets	Dropped Packets	Dropping Rate
Position 1	1	300 Kbps	4689	347	0.068903892
		1.2 Mbps	23847	237	0.009840558
		9.6 Mbps	130499	901	0.006856925
Position 2	2	300 Kbps	4668	369	0.073257892
		1.2 Mbps	24167	204	0.008370604
		9.6 Mbps	130384	1157	0.008795737
Position 3	3	300 Kbps	4576	320	0.065359477
		1.2 Mbps	24153	75	0.003095592
		9.6 Mbps	131783	349	0.002641298
Position 4	4	300 Kbps	4722	294	0.05861244
		1.2 Mbps	24388	5	0.000204977
		9.6 Mbps	130118	55	0.000422515
Position 5	5	300 Kbps	4805	224	0.044541658
		1.2 Mbps	23791	0	0
		9.6 Mbps	134168	5	3.72653E-05
Position 6	6	300 Kbps	4796	233	0.046331279
		1.2 Mbps	23527	0	0
		9.6 Mbps	123780	18	0.000145398
Position 7	7	300 Kbps	3722	902	0.195069204
		1.2 Mbps	20240	0	0
		9.6 Mbps	118700	7	5.89687E-05

Table 7: Distance – 150 ft

		Link Rate	Rx Data Rate	Rx Bits	BER	Eb	Neff
Position 1	1	300 Kbps	234.84 Kbps	164623200	4.70E-07	57.65	35.45
		1.2 Mbps	1.10 Mbps	733965600	3.20E-06	46.16	27.93
		9.6 Mbps	5.91 Mbps	3.94E+09	2.90E-03	26.9	18.92
Position 2	2	300 Kbps	235.15 Kbps	150027200	3.30E-08	57.67	35.59
		1.2 Mbps	1.10 Mbps	774932800	3.60E-06	45.6	28.16
		9.6 Mbps	5.9 Mbps	3.96E+09	2.70E-03	26.99	18.25
Position 3	3	300 Kbps	232.96 Kbps	163770400	6.50E-07	57.67	34.96
		1.2 Mbps	1.10 Mbps	698804000	3.00E-06	45.45	27.96
		9.6 Mbps	5.93 Mbps	4.22E+09	2.30E-03	26.87	18.31
Position 4	4	300 Kbps	226.85 Kbps	154258400	2.00E-07	57.47	35.5
		1.2 Mbps	1.08 Mbps	673318400	2.80E-06	45.61	29.02
		9.6 Mbps	5.84 Mbps	3.76E+09	2.80E-03	26.53	17.95
Position 5	5	300 Kbps	224.67 Kbps	161310400	2.70E-05	57.31	35.47
		1.2 Mbps	1.09 Mbps	758040800	3.80E-05	45.62	27.79
		9.6 Mbps	5.90 Mbps	4.01E+09	1.70E-03	26.75	19.11
Position 6	6	300 Kbps	227.77 Kbps	159211200	1.70E-05	58.11	34.58
		1.2 Mbps	1.11 Mbps	753153600	2.50E-05	46.61	28.23
		9.6 Mbps	5.99 Mbps	4.32E+09	1.50E-03	27.44	19
Position 7	7	300 Kbps	191.86 Kbps	126050400	0	53.34	34.31
		1.2 Mbps	1.05 Mbps	718648000	0	41.57	27.29
		9.6 Mbps	5.66 Mbps	3.45E+09	3.80E-03	22.89	17.85

		Link Rate	Rx Packets	Dropped Packets	Dropping Rate
Position 1	1	300 Kbps	5019	43	0.008494666
		1.2 Mbps	22377	397	0.017432159
		9.6 Mbps	120080	2712	0.022086129
Position 2	2	300 Kbps	4574	34	0.007378472
		1.2 Mbps	23626	389	0.016198209
		9.6 Mbps	120844	2369	0.019226867
Position 3	3	300 Kbps	4993	79	0.01557571
		1.2 Mbps	21305	332	0.015344087
		9.6 Mbps	128606	2439	0.018611927
Position 4	4	300 Kbps	4703	204	0.041573263
		1.2 Mbps	20528	622	0.029408983
		9.6 Mbps	114693	3868	0.032624556
Position 5	5	300 Kbps	4918	270	0.052043177
		1.2 Mbps	23111	515	0.021798019
		9.6 Mbps	122118	3038	0.024273706
Position 6	6	300 Kbps	4854	195	0.038621509
		1.2 Mbps	22962	172	0.007434944
		9.6 Mbps	131668	1111	0.008367287
Position 7	7	300 Kbps	3843	827	0.177087794
		1.2 Mbps	21910	1039	0.045274304
		9.6 Mbps	105091	5666	0.051157037

8.2.1 Outdoor test with external power amplifier

Output power: 8.8dB w/ external amplifier
Tx height: 31"
Rx height: 33"

Table 8: Distance – 425 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped packets
150 Kbps	120.57Kbps	7.3e7	2.2e-7	70.19	40.83	2235/ 217
300 Kbps	212.63Kbps	1.3e8	1.3e-5	62.61	38.01	3909/ 444
600 Kbps	576.82Kbps	3.6e8	1.2e-5	56.11	33.35	10833/ 27
1.2 Mbps	1.12Mbps	6.8e8	1.5e-5	49.78	28.80	20884/ 43
2.4 Mbps	2.09Mbps	1.3e9	1.9e-6	43.86	25.79	38861/ 11
4.8 Mbps	3.70Mbps	2.3e9	3.7e-7	37.75	22.678	70437/ 1
9.6 Mbps	6.05Mbps	3.6e9	9.5e-6	31.29	19.44	111186/ 2

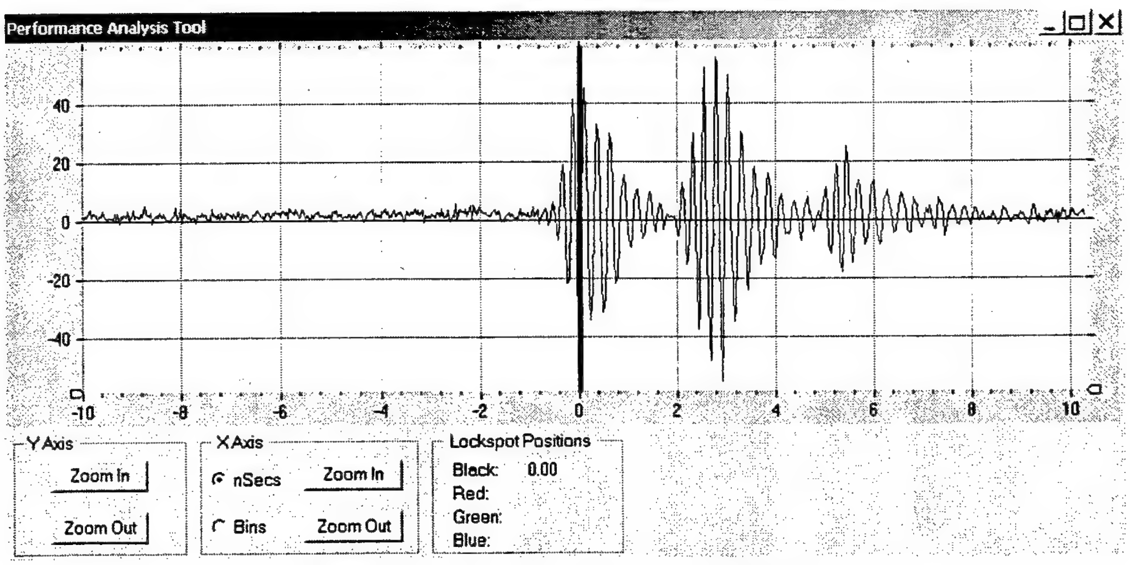

Figure 32. Received signal at 425 ft.

Table 9: Distance – 525 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
150 Kbps	115.89Kbps	7.3e7	0.0	64.06	38.56	2226/ 315
300 Kbps	205.79Kbps	1.2e8	0.0	58.33	36.57	3777/ 573
600 Kbps	579.28Kbps	3.6e8	1.6e-8	52.47	32.10	11197/ 0
1.2 Mbps	1.12Mbps	7.238	3.7e-7	45.85	28.37	22091/ 2
2.4 Mbps	2.09Mbps	1.3e9	1.5e-5	40.09	25.46	40782/ 0
4.8 Mbps	3.71Mbps	2.2e9	1.2e-4	34.01	22.02	68493/ 4
9.6 Mbps	5.55Mbps	3.4e9	6.2e-4	27.52	18.74	102146/ 9681

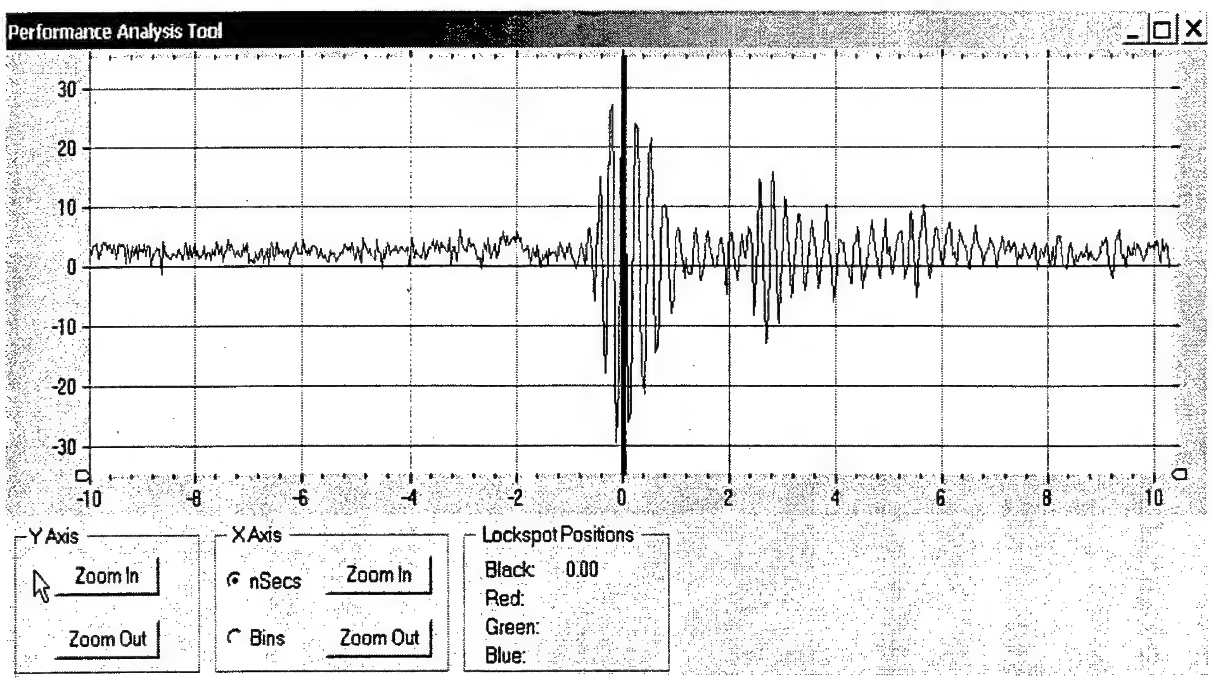

Figure 33. Received signal at 525 ft.

Table 10: Distance – 625 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
150 Kbps	117.25Kbps	7.5e7	1.6e-5	62.10	40.33	2277/ 291
300 Kbps	204.13Kbps	1.3e8	2.1e-5	56.01	35.44	4064/ 647
600 Kbps	574.59Kbps	3.7e8	3.9e-5	49.35	31.63	11159/ 84
1.2 Mbps	1.11Mbps	6.7e8	1.8e-5	43.54	28.66	20392/ 199
2.4 Mbps	2.09Mbps	1.3e9	6.2e-6	37.92	25.47	39411/ 17
4.8 Mbps	3.70Mbps	2.2e9	6.0e-5	31.49	22.09	68375/ 117
9.6 Mbps	6.01Mbps	3.7e9	1.2e-3	24.15	18.02	113695/ 501

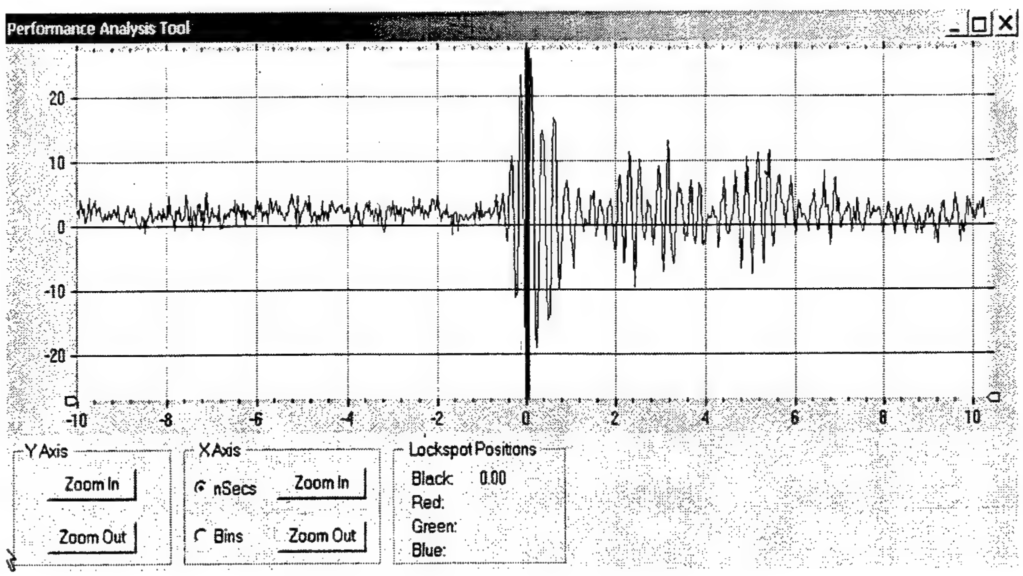

Figure 34. Received signal at 625 ft.

Table 11: Distance – 725 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Nef	Rx Packets/ Dropped Packets
150 Kbps	71.94Kbps	4.4e7	5.2e-5	56.99	37.44	1327/ 1113
300 Kbps	151.53Kbps	9.7e7	1.9e-6	51.11	33.35	2952/ 1660
600 Kbps	501.08Kbps	3.3e8	1.0e-6	44.49	30.71	9930/ 1532
1.2 Mbps	960.94Kbps	6.4e8	6.1e-5	38.38	26.79	19629/ 3173
2.4 Mbps	1.82Mbps	1.2e9	1.0e-3	31.53	23.29	36155/ 5491
4.8 Mbps	3.22Mbps	2.0e9	7.2e-3	26.73	20.98	60968/ 9181
9.6 Mbps	5.22Mbps	3.1e9	3.0e-2	20.54	17.85	96009/ 47710

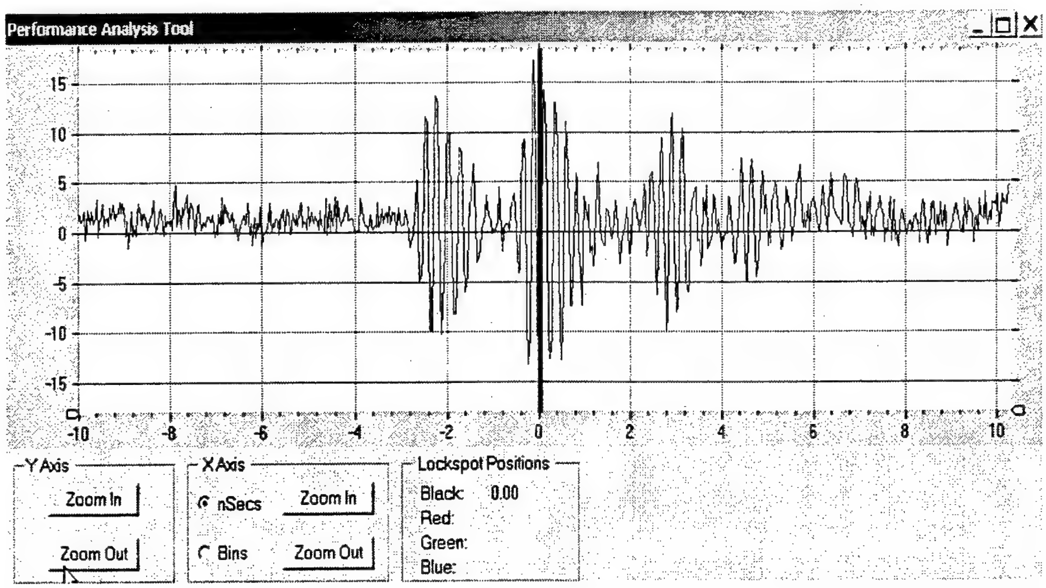

Figure 35. Received signal at 725 ft.

Table 12: Distance – 825 ft

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
150 Kbps	68.00Kbps	4.1e7	0.0	55.71	37.05	1248/ 1178
300 Kbps						
600 Kbps	364.95Kbps	2.2e8	3.6e-8	43.77	29.61	6765/ 3961
1.2 Mbps	704.14Kbps	4.2e8	8.1e-6	37.37	26.98	12945/ 7588
2.4 Mbps	1.29Mbps	7.8e8	5.5e-4	31.04	23.61	23755/ 14710
4.8 Mbps	2.09Mbps	1.6e9	8.0e-3	25.07	20.07	47307/ 36340
9.6 Mbps	3.14Mbps	1.9e9	3.3e-2	16.66	15.78	57755/ 53280

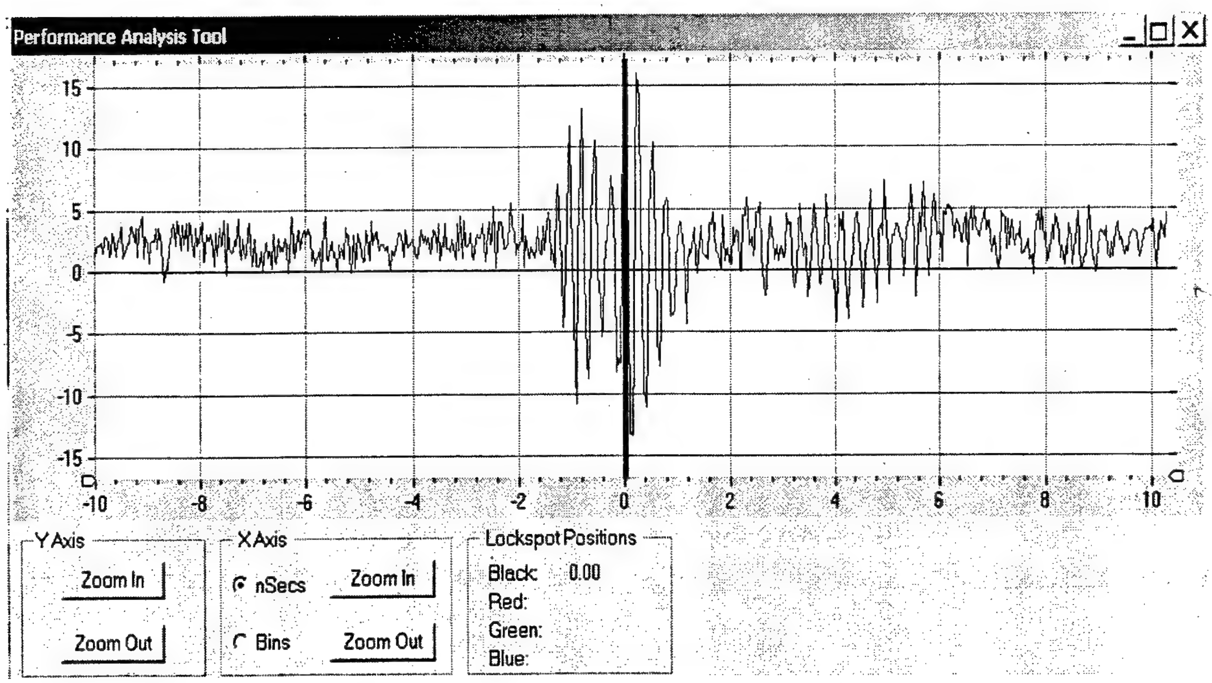

Figure 36. Received signal at 825 ft.

8.2.2 Indoor test without external power amplifier

Output power: -12.2dB
Tx 1 height: 52"
Tx 2 and 3 height: 31"
Rx height: 33"

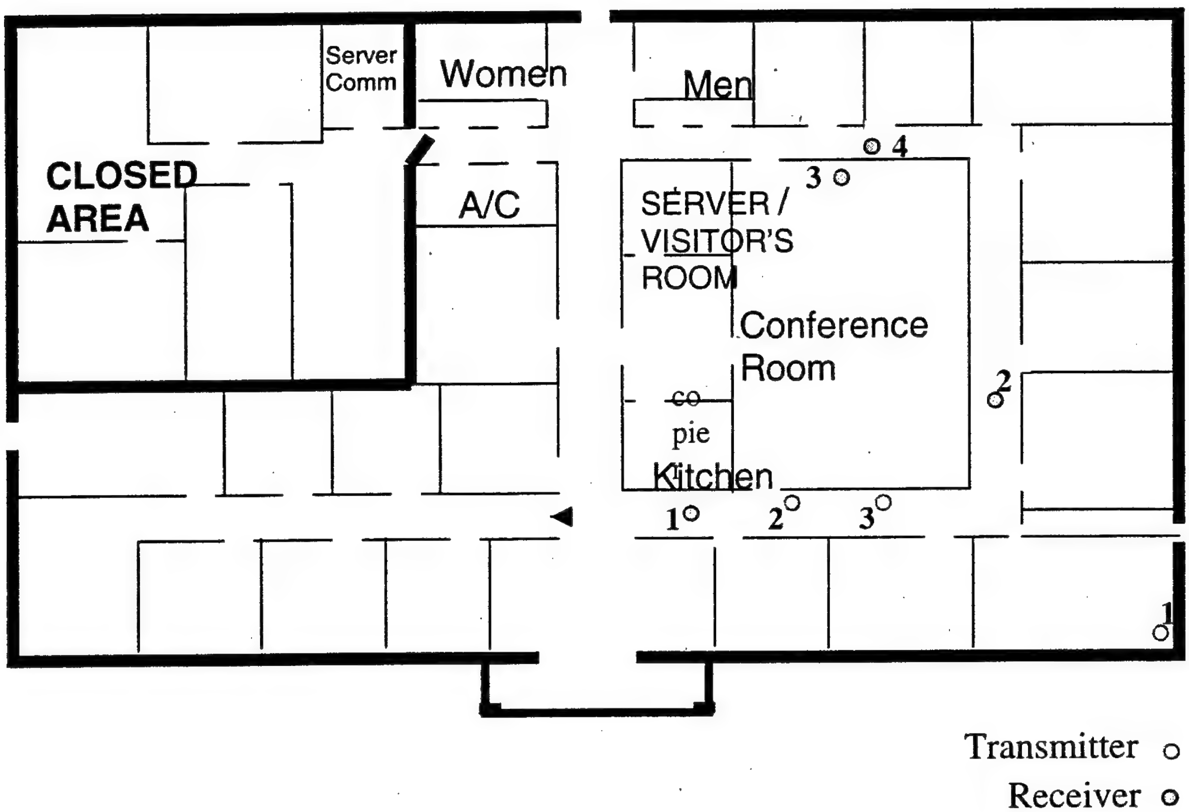

Figure 37. Indoor Area Map.

Table 13: Distance from Tx1 to Rx1

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
300 Kbps	236.56 Kbps	1.5e8	0.0	56.52	34.59	4450/ 1
600 Kbps	578.58 Kbps	3.5e8	0.0	50.51	31.09	10672/ 2
1.2 Mbps	1.12 Mbps	7.1e8	0.0	42.88	27.88	21516/ 5
2.4 Mbps	2.09 Mbps	1.5e9	4.9e-8	38.13	24.76	45118/ 16
4.8 Mbps	3.70 Mbps	2.3e9	4.2e-5	30.60	22.19	69670/ 11
9.6 Mbps	6.04 Mbps	3.7e9	2.4e-3	25.58	18.56	112352/ 14

Table 14: Distance from Tx1 to Rx2

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
300 Kbps	235.10 Kbps	1.4e8	0.0	54.12	34.02	4358/ 31
600 Kbps	431.94 Kbps	2.6e8	0.0	47.84	30.63	7954/ 2693
1.2 Mbps	836.66 Kbps	5.7e8	8.8e-9	42.03	27.91	17371/ 5835
2.4 Mbps	1.56 Mbps	9.6e8	3.1e-6	33.95	24.34	29285/ 9981
4.8 Mbps	2.77 Mbps	1.8e9	2.9e-4	30.23	21.56	56372/ 19034
9.6 Mbps	4.50 Mbps	2.9e9	6.4e-3	23.76	18.52	87488/ 29834

Table 15: Distance from Tx2 to Rx3

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
300 Kbps	236.33 Kbps	1.7e8	0.0	57.91	34.52	5231/ 10
600 Kbps	578.69 Kbps	4.0e8	0.0	51.80	30.93	12156/ 0
1.2 Mbps	1.12 Mbps	6.8e8	0.0	44.68	27.47	20665/ 0
2.4 Mbps	2.09 Mbps	1.5e9	1.8e-7	38.61	24.36	45285/ 0
4.8 Mbps	3.71 Mbps	2.5e9	1.9e-5	33.35	21.87	76621/ 0
9.6 Mbps	6.04 Mbps	3.6e9	5.0e-4	26.92	18.16	111032/ 0

Table 16: Distance from Tx3 to Rx4

Link Rate	Rx Data Rate	Rx bits	BER	Eb	Neff	Rx Packets/ Dropped Packets
300 Kbps	232.70 Kbps	2.6e8	0	63.70	39.68	8038/ 142
600 Kbps	578.39 Kbps	3.5e8	2.8e-9	59.79	36.73	10739/ 2
1.2 Mbps	1.12 Kbps	7.0e8	5.5e-8	53.64	32.73	21438/ 1
2.4 Mbps	2.09 Mbps	1.5e9	3.6e-5	47.90	28.01	45912/ 5
4.8 Mbps	3.70 Mbps	2.4e9	3.3e-4	39.71	24.31	71361/ 8
9.6 Mbps	6.04 Mbps	4.0e9	1.6e-3	35.56	22.04	122288/ 20

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